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Dissertação orientada pela Professora Doutora Tânia Fernandes

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Abstract

Learning to read is an intensive visual activity that, through perceptual learning, leads to changes on early visual brain areas, including the *primary occipital cortex, V1*. The *Ebbinghaus* illusion is known to depend on V1 functioning. Furthermore, previous studies suggest that children are less susceptible to this illusion than adults. Although this phenomenon has mostly been attributed to cognitive development, a recent study showed that it could be attributed to schooling, given its relation with the number of years of education in Himba people. In this thesis, we hypothesized that literacy, instead of schooling, is the relevant cultural variable influencing susceptibility to this illusion. We explored this hypothesis in two experiments. In Experiment 1, we examined literate, ex-illiterate and illiterate adults, matched in age and sex and from the same socioeconomic and cultural background. In Experiment 2, we compared two groups of children matched in age and cognitive development, who differed only in schooling/literacy: pre-literate preschoolers vs. first-grade children learning to read. Experiment 2 provided convergent evidence and, by comparing children and adult readers, allowed to examine if development influences susceptibility to this illusion. Participants performed a size discrimination task, where they decided which of two circles was the largest. In the first block, these circles where surrounded by other circles or *inducers*, which could have a *congruent* or *incongruent size* relative to the inner target circles (that is, the larger inner circle surrounded by large or by small inducers, respectively). In the second block, participants performed the same task *without inducers* to ensure that any difference to be found between-groups in the block with inducers would not be due to differences in veridical size discrimination abilities. As expected, non-readers were less susceptible to the illusion than readers, which evidences the impact of learning to read in early visual processing.

Keywords: Ebbinghaus illusion; Titchener circles; visual context integration; learning to read; literacy; schooling; development; culture; early visual processing; primary visual cortex; V1.

Resumo

Aprender a ler é uma atividade visual intensa que leva a mudanças em áreas visuais precoces, incluindo o *córtex occipital primário, V1.* A ilusão de *Ebbinghaus* depende do funcionamento de V1. Ademais, estudos prévios sugeriram que as crianças são menos suscetíveis a esta ilusão do que adultos. Apesar de este fenómeno ser tendencialmente atribuído ao desenvolvimento cognitivo, um estudo recente demonstrou que este podia ser atribuído à escolarização, uma vez que se observou uma relação entre os anos de escolarização em pessoas Himba e a suscetibilidade a esta ilusão. Nesta dissertação, hipotetizou-se que a literacia, ao invés da escolarização, é a variável cultural relevante que influencia a suscetibilidade. Explorou-se esta hipótese em duas experiências. Na Experiência 1, examinou-se adultos letrados, ex-iletrados e iletrados, emparelhados em sexo, idade, estatuto socioeconómico e pertencentes à mesma cultura. Na Experiência 2, comparou-se dois grupos de crianças, emparelhados em idade e desenvolvimento cognitivo, que diferiam apenas em escolarização/literacia: crianças pré-letradas em jardins de infância e crianças do 1º ano a aprender a ler. A Experiência 2 serviu para fornecer convergência evidente e também permitiu examinar se o desenvolvimento influencia a suscetibilidade à ilusão, através da comparação entre crianças e adultos leitores. Os participantes desempenharam uma tarefa de discriminação de tamanho, em que tinham que decidir qual de dois círculos era maior. No primeiro bloco, os círculos eram rodeados por outros círculos, ou *indutores*, que podiam ter tamanho *congruente* ou *incongruente* relativamente ao tamanho do círculo central alvo (isto é, o círculo central maior podia estar rodeado de indutores grandes ou pequenos, respetivamente). No segundo bloco, os participantes desempenharam a mesma tarefa *sem indutores* para assegurar que qualquer diferença encontrada entre grupos não se deve a diferenças em habilidades de discriminação de tamanho verídico. Como era esperado, os não-leitores foram menos suscetíveis à ilusão do que os leitores, o que evidenciou o impacto da literacia no processamento visual precoce.

Resumo alargado

As diferenças culturais na cognição, nomeadamente na perceção visual, têm surpreendido investigadores desde o início do século passado (e.g. Luria, 1931; 1933), e continuam a ser estudadas hoje em dia. No entanto, o foco da investigação nesta área tende a ser cultura a nível macro, isto é, procura-se compreender como as caraterísticas da cultura, por exemplo, no que toca à maneira como as interações sociais são estabelecidas, influenciam a cognição de maneira geral (e.g. Varnum e col., 2010), ao invés de se focar na cultura a nível micro, isto é, procurar compreender como objetos culturais específicos dentro da cultura interagem com mecanismos neurocognitivos específicos. No entanto, estudar estas variáveis culturais a nível micro é importante, uma vez que diferentes objetos culturais dentro da mesma cultura podem ter um impacto dissociado em mecanismos cognitivos distintos, pelo que só através do estudo de variáveis culturais a nível micro é possível verdadeiramente compreender a interação entre a cultura e estes mecanismos. Na presente dissertação, estudámos como uma variável cultural a nível micro, a aprendizagem da leitura, influencia mecanismos neurocognitivos envolvidos no processamento visual precoce.

Estudos prévios sugerem que a literacia tem impacto em áreas cerebrais visuais precoces, incluindo o córtex occipital primário (V1; e.g. Swed e col., 2011; 2012; 2014; Chang e col., 2015) através de processos de aprendizagem percetiva (i.e. a experiência extensiva na perceção de estímulos leva a adaptação das áreas visuais a estes estímulos encontrados frequentemente devido a plasticidade sináptica dependente da experiência; Gilbert & Li, 2012; Gilbert, Sigman & Crist, 2001; Sagi, 2011; Sasaki, Nanez & Watanabe, 2009). Por exemplo, demonstrou-se que os adultos letrados mostram maior ativação fMRI em V1 para estímulos de palavras em que certos componentes de cada letra foram apagados, comparados com estímulos controlo bem emparelhados em que certos componentes de cada elemento foram apagados (Szwed e col., 2011; 2014), e também maior ativação para letras e símbolos emparelhados com letras em comparação com versões rodadas das mesmas formas (Chang e col., 2015). Mais importante, existe também evidência que sugere que a literacia tem um impacto na força das conexões horizontais de longa distância entre células em V1: Szwed e col. (2012) demonstraram que adultos iletrados e ex-iletrados são melhores que adultos letrados numa tarefa de integração de contornos, que tende a ser usada para medir a força destas conexões (Gervan & Kovács, 2010; Hadad e col., 2010). Estas mudanças decorrentes da literacia poderão ter consequências em outras tarefas visuais que dependem dos mesmos processos visuais precoces, como é o caso com o paradigma da ilusão de *Ebbinghaus* (i.e. o tamanho percebido de um círculo central é modelado por círculos adjacentes; Ebbinghaus, 1901), uma vez que esta ilusão depende do funcionamento de áreas visuais precoces, especificamente o córtex visual primário (V1; Chen e col., 2018; Schwarzkopf & Rees, 2013; Song e col., 2011), e foi sugerido também depender de conexões horizontais de longa distância entre células em V1 (Kovács e col., 1999; Li, Piëch & Gilbert, 2006).

O possível impacto da literacia na suscetibilidade à ilusão de Ebbinghaus é apoiado por estudos do desenvolvimento que sugerem uma trajetória de desenvolvimento na suscetibilidade a esta ilusão, sendo que a suscetibilidade aumenta com a idade: crianças são menos afetadas pela ilusão do que adultos (Hadad, 2018; Experiência 2; Kaldy & Kovács, 2003); a magnitude da ilusão aumenta dos 4 aos 12 anos de idade, sendo que as maiores diferenças ocorrem entre os 4-5 e os 6-7 anos (Hadad, 2018; Experiência 1; Imada e col., 2013; Weintraub, 1979; Zannuttini, 1996); no entanto, Doherty e col. (2010) observaram que as crianças não são afetadas pela ilusão antes dos seis anos de idade, pelo que depois disto, a magnitude da ilusão começa a aumentar com a idade. Estes resultados são tendencialmente atribuídos ao papel da maturação, sendo que se racionalizou que a sensitividade ao contexto visual aumenta com a idade. No entanto, estas diferenças principalmente evidentes entre os 4-5 e os 6-7 anos poderão ser melhor explicadas pelo impacto de uma variável cultural a nível micro, a escolarização ou literacia, uma vez que é nestas idades que as crianças entram na escola e começam a aprender a ler. De facto, o impacto de práticas culturais nesta ilusão já foi sugerido anteriormente.

Estudos culturais consistentemente observam que as pessoas em sociedades industrializadas, como os Ingleses, são mais suscetíveis a esta ilusão do que pessoas em sociedades não industrializadas, como os Himba da Namíbia (Bremner e col., 2016; Caparos e col., 2011; Davidoff, Fonteneau & Goldstein, 2008; de Fockert e col., 2007). Estas diferenças foram explicadas, por exemplo, com a exposição a ambientes visualmente densos. Em sociedades industrializadas, as ruas são marcadas por cenários com muitos elementos, o que, segundo Miyamoto, Nisbett e Massuda (2006) e Nisbett e Miyamoto (2005), promove um tipo de processamento visual holístico, isto é, em que a forma com que um elemento visual é percecionado está dependente do contexto em que esse elemento visual se insere. Desta forma, Caparos e col. (2011) hipotetizaram que a exposição a estes ambientes densos iria aumentar a integração do contexto visual na ilusão de Ebbinghaus. Para testar esta hipótese, investigaram a suscetibilidade à ilusão de Ebbinghaus com participantes ingleses, japoneses, e participantes Himba que estavam divididos em dois grupos: Himba urbano, que eram Himba que cresceram em ambientes urbanos com ambientes cheios, e Himba tradicional, que eram Himba que raramente, ou nunca, tinham saído das suas aldeias. Estes autores verificaram que os japoneses foram os mais suscetíveis à ilusão, e os Himba tradicional os menos suscetíveis, enquanto os Ingleses e os Himba urbano estavam no meio e não diferiram um do outro, tendo sido sugerido que a exposição destes Himba urbano a ambientes densos promoveu maior suscetibilidade à ilusão de Ebbinghaus em comparação com os Himba tradicional que cresceram em aldeias com ambientes não densos. Doherty e col. (2010) também sugeriram que uma variável cultural, a exposição a informação pictorial, estava envolvida não só na diferença na suscetibilidade à ilusão entre crianças de diferentes idades encontradas no seu estudo, como também nas diferenças entre participantes Himba e Ingleses. Segundo estes autores, as crianças precisam de muita experiência a interpretar 3D em imagens 2D antes de se tornarem suscetíveis à ilusão. Da mesma forma, os Himba seriam menos sucetíveis à ilusão porque não têm acesso a informação pictorial. Deve-se notar que os Himba, apesar de menos sucetíveis à ilusão, não são imunes à mesma, o que sugere que a exposição a informação pictorial não é necessária para desencadear a suscetibilidade à ilusão, ao contrário do que foi sugerido por Doherty e col. (2010), e, assim, esta variável poderá ter um papel moderador, mas não desencadeador, da ilusão.

No entanto, nestes estudos culturais, adultos Himba com diversos níveis de escolarização (de 0 a 12 anos) foram comparados com estudantes universitários Ingleses (com pelo menos 12 anos de educação), e, assim, além da pertença a culturas diferentes, os dois grupos diferiram nos níveis de escolarização, um factor que influencia processos percetivos (Myamoto e col., 2006; Ventura, e col., 2008). Desta forma, a escolarização poderá estar a contribuir para as diferenças culturais observadas.

Tendo isto em conta, Bremner e col. (2016) examinaram a suscetibilidade à ilusão de Ebbinghaus em participantes Ingleses e Himba (Tradicional e Urbano) desde os três anos até à idade adulta, tendo em conta os anos de escolarização e a exposição a ambientes densos. Desde os três aos 10 anos, os participantes Himba demonstraram a menor suscetibilidade à ilusão. As crianças de três a seis anos de idade demonstraram a menor suscetibilidade à ilusão, independentemente da cultura. Foi apenas a partir dos sete anos de idade que as diferenças culturais começaram a ser observadas (como já tinha sido observado num estudo que comparou a suscetibilidade à ilusão de Ebbinghaus em crianças Japonesas e Americanas; Imada e col., 2013). Crianças Himba em ambientes rurais (Himba Tradicional) foram menos sucetíveis à ilusão do que qualquer outro grupo, e as crianças Inglesas foram as mais suscetíveis, enquanto os Himba Urbano estavam no meio. As diferenças na exposição a ambientes densos não foram o fator principal subjacente a diferenças culturais, uma vez que não se encontrou uma correlação significativa entre a suscetibilidade à ilusão e a exposição a ambientes urbanos. No entanto, mais importante, o número de anos de escolarização estava significativamente correlacionado com a suscetibilidade à ilusão, e a correlação manteve-se quando se controlou a exposição a ambientes urbanos e a idade. No entanto, estes autores não separaram os efeitos da escolarização de um modo geral e da literacia. No presente estudo, procurámos estudar especificamente o efeito da literacia na suscetibilidade à ilusão de Ebbinghaus, dadas as evidências já mencionadas que a literacia influencia áreas visuais precoces, como V1 (e.g. Szwed e col., 2011; 2012), e de que a ilusão de Ebbinghaus está dependente do funcionamento em V1 (e.g. Schwarzkopf & Rees, 2013).

O papel da literacia na suscetibilidade à ilusão de Ebbinghaus foi examinado em duas experiências, uma com adultos e outra com crianças. Na Experiência 1, para separar os efeitos da escolarização e da literacia, comparámos adultos iletrados, ex-iletrados (isto é, adultos que aprenderam a ler na vida adulta e que não foram escolarizados) e letrados (adultos letrados e escolarizados), emparelhados em idade, sexo, estatuto socioeconómico e pertencentes à mesma cultura. Na Experiência 2, comparámos dois grupos de crianças, emprelhados em idade e desenvolvimento cognitivo, que diferiam apenas na escolarização/literacia: crianças pré-letradas em jardins de infância e crianças do 1º ano escolar a aprender a ler. Evidência convergente nestas duas experiências permitiu testar de maneira robusta se a aprendizagem da leitura era, de facto, o principal responsável pelas diferenças na suscetibilidade à ilusão de Ebbinghaus. Ademais, a comparação entre a magnitude da ilusão para adultos e para crianças permitiu examinar se o desenvolvimento neuronal tem alguma influência na magnitude da ilusão.

Para testar o efeito da literacia na integração do contexto visual, utilizámos uma tarefa de discriminação de tamanho em que os participantes tinham que decidir qual de dois círculos apresentados era maior. Os círculos podiam estar rodeados de indutores (*bloco com indutores*) ou apresentados isoladamente (*bloco sem indutores*). No bloco com indutores, utilizámos dois tipos de contextos: *contextos congruentes*, em que dois círculos centrais com diferentes tamanhos eram apresentados, sendo que o círculo central maior estava sempre rodeado de indutores grandes e o círculo central menor estava rodeado de indutores pequenos; e *contextos incongruentes*, em que o círculo central maior estava sempre rodeado de indutores pequenos e o círculo central menor estava rodeado de indutores grandes. O contexto congruente representava a ilusão de Ebbinghaus clássica, uma vez que o efeito do contexto é prejudicador, dado que o círculo fisicamente maior rodeado de indutores grandes iria ser subestimado e o círculo fisicamente menor iria ser sobrestimado. O contexto incongruente servia para apoiar a discriminação e tinha como objetivo verificar se, de facto, os leitores eram mais sensíveis ao contexto: se for este o caso, estes participantes iriam ser piores na condição de contexto congruente mas melhores na condição de contexto incongruente. Por último, o bloco sem indutores representava uma condição controlo que tinha como propósito avaliar a capacidade discriminação verídica dos participantes. Em ambos os blocos, a diferença de tamanho real dos círculos a ser comparados variava em passos de 4%, e podia ser 2%, 6%, 10%, 14% ou 18%.

Hipotetizou-se que, em ambas as experiências, não-leitores (Experiência 1, adultos iletrados; Experiência 2, crianças pré-letradas) iriam ser menos suscetíveis ao contexto na discriminação de tamanho do que os leitores (Experiência 1, adultos ex-iletrados e letrados; Experiência 2, crianças do 1º ano a aprender a ler), no entanto, iriam ser tão capazes de desempenhar discriminação de tamanho verídica (sem indutores) como os leitores. Estas diferenças poderiam ser mais acentuadas em diferenças de tamanho real mais pequenas.

Como era esperado, verificou-se que a literacia teve um efeito na suscetibilidade à ilusão de Ebbinghaus: não-leitores foram menos suscetíveis à ilusão de Ebbinghaus do que os leitores. Isto significa que adultos iletrados foram menos sensíveis ao contexto congruente em comparação adultos ex-iletrados e letrados na Experiência 1, e crianças pré-letradas foram menos sensíveis a este contexto em comparação com crianças do 1º ano a aprender a ler. Estas diferenças foram mais acentuadas em diferenças de tamanho menores. No que toca ao contexto incongruente, a literacia teve um efeito na Experiência 1, sendo que, devido à menor sensitividade ao contexto, adultos iletrados tiveram um pior desempenho neste contexto do que adultos ex-iletrados e letrados. No entanto, não se verificou um efeito de literacia na Experiência 2, as crianças pré-letradas não diferiram das crianças do 1º ano no contexto incongruente. Em ambas as experiências, os grupos nunca diferiram no que toca à discriminação de tamanho verídica (sem indutores).

Isto demonstra que a literacia tem um impacto em habilidades visuais de integração do contexto, e, mais especificamente, no processamento visual precoces, realçando o papel de uma variável cultural a nível micro em moldar a experiência visual humana, através de processos de aprendizagem percetiva.

Adicionalmente, os nossos resultados, de modo geral, demonstram que as diferenças em habilidades visuais entre culturas não devem ser atribuídas à cultura em si, mas sim a práticas culturais que podem levar a aprendizagem percetiva, isto é, podem levar à adaptação de circuitos plásticos no sistema visual para às experiências que são encontradas de maneira recorrente, como seria o caso durante a aprendizagem da leitura. Da mesma forma, diferenças entre crianças de diferentes idades podem não refletir o papel da maturação, mas sim o papel de práticas culturais que aparecem em diferentes idades, como é o caso com a entrada na escola e a aprendizagem da leitura para crianças de seis anos.

Palavras-chave: ilusão de Ebbinghaus; círculos de Titchener; integração visual do contexto; aprendizagem da leitura; literacia; escolarização; desenvolvimento; cultura; processamento visual precoce; córtex visual primário; V1.

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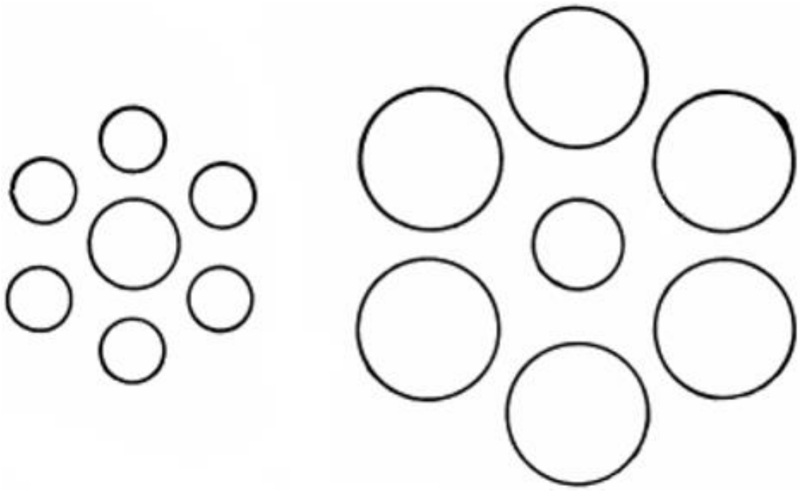
Introduction

The *Ebbinghaus illusion* or Titchener circles is a perceptual[1] illusion (Ebbinghaus, 1902; Titchener, 1901), where the perceived size of a central target is influenced by the surrounding information[2]. As shown in Figure 1, when two inner circles of equal size are presented, the size of the inner circle tends to be *underestimated* when surrounded by *larger* circles or *inducers* and *overestimated* when surrounded by smaller inducers (e.g., Girgus, Coren, & Agdern, 1972; Massaro & Anderson, 1971). This phenomenon illustrates a very general finding: perception of an object is influenced by the surrounding context.

Figure 1. *Representation of the Ebbinghaus illusion (adapted from Titchener, 1901, p. 169)*



Ever since this illusion has caught the eye of researchers, investigation has examined the factors that play a role in susceptibility to it. Most research has focused on the sensorial properties of the stimuli (e.g., the size of and the distance between target and inducers; number of inducers; e.g., Jaeger & Klahs, 2015; Roberts, Harris, Yates, 2005), which has been fruitful

[1] In contrast to optical illusions which can be called sensory illusions (occurring at the eyes-level as the waterfall effect), perceptual illusions arise from misinterpretation of sensory information at the brain level (cf. Gregory, 1968).
[2] Whereas most research on the Ebbinghaus illusion has used circles, similar effects were found with other geometric shapes like squares (e.g., Todorovic & Jovanovic, 2018).

in enlightening the cognitive mechanisms underlying this illusion, regardless of the observer.

More important, in the previous decade, other research has focused on the role of *psychosocial* variables, such as culture at *macro-level* (e.g., Eastern vs. Western participants: Doherty, Tsuji, & Phillips, 2008; remote African Himba vs. industrialized European British participants: e.g., de Fockert, Davidoff, Fagot, Parron, & Goldstein, 2007), gender (e.g., Phillips, Chapman, & Berry, 2004; but see, Doherty, Campbell, Tsuji & Philips, 2010; Shaqiri et al., 2018), and development (e.g., Bremner et al., 2016; Doherty et al., 2010). The focus of this research has often been on culture per se and not on how culture interacts with the neurocognitive mechanisms of visual object processing, which we examined in this work.

The present dissertation focused on a psychosocial, cultural variable at *micro-level* (that is, a cultural object inside culture); specifically, learning to read or *literacy acquisition.* This is a cultural invention too recent in the history of humankind to have been entrenched in the human genome but whose acquisition leads to deep changes in visual object processing (cf. Dehaene, 2009; for a recent review, see, Dehaene, Cohen, Morais, & Kolinsky, 2015). In this thesis, we tested whether learning to read enhances the magnitude of the Ebbinghaus illusion and whether the influence of this cultural object is stronger than the one of cognitive development.

Cognitive mechanisms of the Ebbinghaus illusion

Far before the potential role of psychosocial variables has begun to be investigated, almost 40 years of research have shown that perceptual properties of the stimuli influence the Ebbinghaus illusion. Two cognitive mechanisms have been advanced as its locus.

The size contrast account

According to the *size contrast theory* (Massaro & Anderson, 1971), the surrounding inducers represent a comparison standard in the process of size judgment of the central target: when surrounded by larger inducers, the observer exaggerates the relative smallness of the inner circle (*size underestimation*); when surrounded by smaller inducers, the observer exaggerates the relative largeness of the inner circle (*size overestimation*). Based on this account, the locus of the Ebbinghaus illusion is at high-level structures related to size comparison and inferential processes (Coren & Miller, 1974; de Fockert et al, 2007; Massaro & Anderson, 1971).

Indeed, the Ebbinghaus illusion is modulated by size and number of inducers: the larger (or smaller) the inducers relative to the inner target, the harder would be to escape from the illusion (Girgus et al., 1972; Massaro & Anderson, 1971; Weintraub & Schneck, 1986). Also, more small inducers provide stronger evidence for the presence of size contrast, augmenting size overestimation (Massaro & Anderson, 1971). Furthermore, suggesting the role of high-level information, the Ebbinghaus illusion is enhanced by figural similarity between target and inducers (e.g., more illusion when the inner circle is surrounded by circles than diamonds) possibly because the perceptual system is more likely to compare similar stimuli (Coren & Enns, 1993; Coren & Miller, 1974; Choplin & Medin, 1999; de Fockert et al., 2007; Deni & Brigner, 1997; Rose & Bressan, 2002). However, this latter research has been criticized for the lack of a clear definition of similarity and for confounding shape, size, and contour manipulation (Choplin & Medin, 1999; Rose & Bressan, 2002).

Consistent with this account, attention has been suggested to play a role in the susceptibility to the Ebbinghaus illusion, which denotes the involvement of feedback processes: Shulman (1992) demonstrated that, when a central circle was surrounded by both large and small inducers, size underestimation occurred when the participant attended to the large inducers only, whereas there was no illusion when the participant attended to the small inducers. Also, Axelrod, Schwarzkopf, Gilaie-Dotan and Rees (2017) found a robust correlation between the magnitude of this illusion and gray matter density in the parahippocampal cortex, a high-level brain region known to underpin topographical, visuospatial representations.

Although size contrast mechanisms might operate at least in some conditions of the

Ebbinghaus illusion, the size-contrast proposal is oversimplistic and cannot explain several findings. For example, size and number of inducers interact with distance between the inner target and inducers (Girgus et al., 1972; Jaeger & Klahs, 2015) in a way not predicted by Massaro and Anderson's (1971) proposal: regardless of size, increasing inducers' distance causes underestimation of the target size (e.g., Roberts et al., 2005). Furthermore, Jaeger (1977, 1978) showed that, when the inner target and the inducers were presented in sequence, the Ebbinghaus illusion was severely reduced: There was no longer size overestimation when the target was surrounded by smaller inducers but, when surrounded by larger inducers, size underestimation was still present, albeit heavily diminished, which suggests that size overestimation and underestimation are not two sides of the same coin.

Recent studies provided further evidence that this illusion is not necessarily about size comparison. By adopting the *flash-lag effect* (FLE[3]), in a way that two configurations of inducers with different retinal (physical) size (one of large inducers, other of small inducers) appeared to be of the same size, Takao, Clifford and Watanabe (2019) showed that size distortions can indeed be induced by the FLE but they do not modulate the Ebbinghaus illusion. In other words, the Ebbinghaus illusion was about the retinal size of inducers and not about the perceived size. Also, size contrast does not seem to be even necessary for the Ebbinghaus illusion to occur. Cheng, Qiao, Wang and Jian (2018) found that size estimation of the target is modulated by context, even when it is suppressed from awareness through *continuous flash suppression, CFS* (a technique derived from binocular rivalry, Tsuchiya & Koch, 2005, where a stimulus presented to one eye is suppressed from conscious perception due to high-contrast and dynamic masking images being simultaneously presented to the other eye). Participants still experienced the illusion, even when not consciously aware of the presence of the inducers.

[3] FLE is a phenomenon about illusory misalignment of two (aligned) stimuli (Eagleman, 2000; Watanabe & Yokoi, 2006). When a moving and a flashed stimulus are presented in spatial alignment, a compelling spatial dissociation between the physically given stimulus and the perceived stimulus occurs.

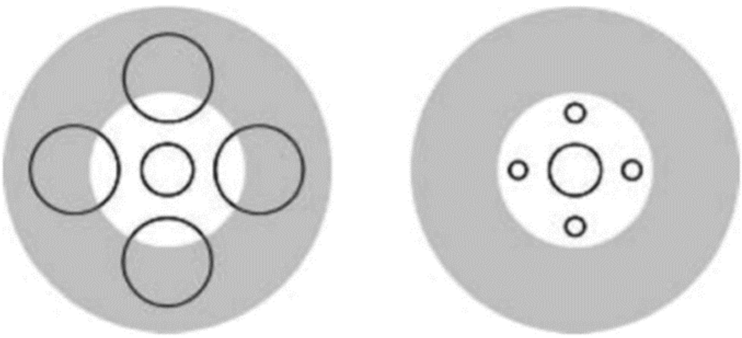
The contour interaction account

The *contour interaction theory* (Jaeger, 1978; Jaeger & Klahs, 2015) suggests that the Ebbinghaus illusion is about low-level interactions (at cortical level) between visual contours. The neural representations of contextual contours, adjacent to the central target, perceptually *attract* the edges of the target, inducing size overestimation, whereas the neural representations of contextual contours relatively far away from the target, perceptually *repel* its edges, inducing size underestimation. Therefore, small inducers produce attraction because in a sensory-level topographic representation of the figure, there are interactions between these close contours, which diminish their separation. Likewise, the presence of more inducers imply more contours, and hence, stronger contour interaction effects (e.g., Roberts et al., 2005). Large inducers produce repulsion due to sensory interactions, with the critical interactions being those between representations of more distant contours (Jaeger & Klahs, 2015).

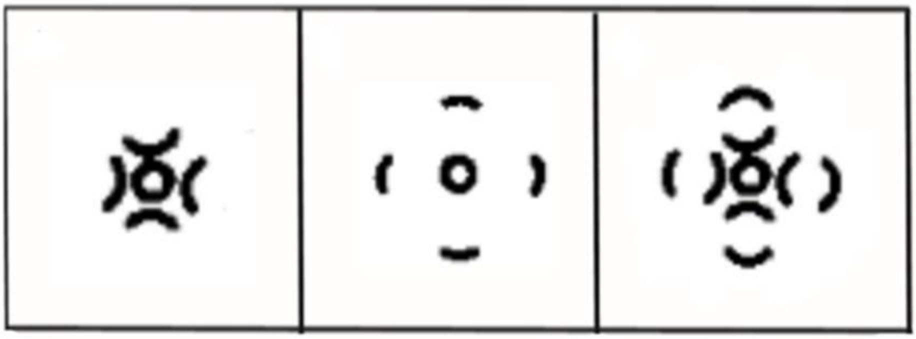
Note that increasing the distance between large inducers and target results in a larger illusion (Ehrenstein & Hamada, 1995; Jaeger & Grasso, 1993; Jaeger, Klahs & Newton, 2014; Roberts et al., 2005), because both the nearest and the outer contours of large inducers will contribute to the contour interaction effect (Jaeger, 1978; Rose & Bressan, 2002; Sherman & Chouinard, 2016). Thus, even when the inner contours of large and of small inducers are at the same distance from the inner target, the inner contours of both types of inducers lead to attraction, but large inducers will still cause greater repulsion because their outer contours fall in the repulsion zone represented in Figure 2A. Therefore, as shown in Figure 2B, removing intermediary edges while keeping both the inner and outer contours induces size underestimation (due to contour repulsion), but less than when only outer contours are presented (Weintraub & Schnek, 1986). Further support for the contour interaction account comes from psychophysical studies demonstrating directly that nearby contours attract and contours at intermediate distances repel (e.g. Badcock & Westheimer, 1985; Bondarko & Danilova, 1999).

Figure 2. *Different configurations of Ebbinghaus stimuli*

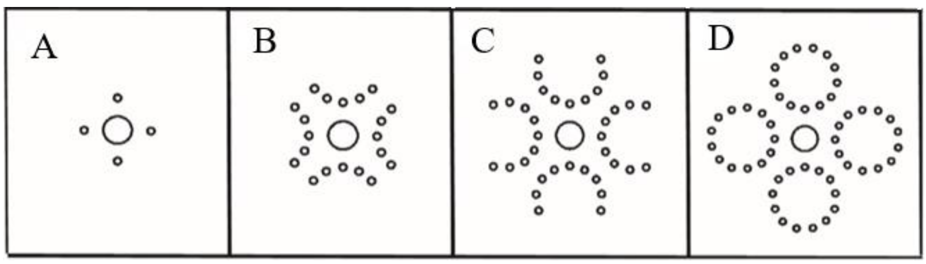
(A) *Putative regions of repulsion in gray, surrounding an inner area of attraction*



(B) *From left to right, the central circle is surrounded: only by inner contours; only by outer contours; by both inner and outer contours*



(C) *Central circles surrounded by small inducers that gradually form a larger circle: A and B result in size overestimation, C and D result in size underestimation*



As aforementioned, at large distances, small inducers lead to underestimation of target size and not to overestimation (Girgus et al., 1972; Jaeger, 1978; Knol, Huys, Sarrazin & Jirsa, 2015; Roberts et al., 2005). The contour interaction account (Jaeger, 1978; Jaeger & Klahs, 2015) is able to accommodate this evidence. Furthermore, increasing the number of small inducers does not systematically lead to size overestimation of the target. When the target is surrounded by small inducers presented at multiple distances from the center, the Ebbinghaus illusion (that is, target size overestimation) does not increase as it would be expected from the size contrast account (Massaro & Anderson, 1971); instead, it becomes weaker (in fact, null), because the additional contours at farther distances from the target lead to a repulsive effect which counteracts the attractive effect of the nearer contours (Todorovic, & Jovanovic, 2018; Experiment 2). When the contour of large inducers was replaced by a varied number of small circles in a way that those small circles gradually completed the large inducers, as shown in Figure 2C, the perceived size of the inner target was overestimated with few small circles at shorter distances (due to contour attraction) but it was underestimated when the number of small circles increased, completing the shape of large inducers, due to distant separations of contours resulting in repulsion (Jaeger & Klahs, 2015). Also, inducers of equal size as the target do not have an effect at near distances but lead to size underestimation at farther distances (Jaeger & Grasso, 1993, Roberts et al., 2005).

Moreover, increasing visual similarity by manipulating the lightness of target and inducers (e.g., black target with gray inducers vs. black target with black inducers, respectively) or shape (e.g., hexagonal target surrounded by circles or triangles) does not lead to a larger Ebbinghaus illusion (Jaeger et al. 2014; Jaeger & Grasso, 1993; Roberts et al., 2005; Rose & Bressan, 2002), which argues against the notion that similarity facilitates size comparison, resulting in more illusion. The existence of verbal labels that distinguish target from inducers did neither exert any influence in the Ebbinghaus illusion (de Fockert et al., 2007).

The temporal locus of the Ebbinghaus illusion

In line with the contour interaction account (Jaeger, 1978), psychophysical evidence suggests that this illusion occurs early on in visual processing. Indeed, the Ebbinghaus illusion influences size estimation of the inner target even when observers are not aware of the inducers due to CFS or backward masking (Cheng et al., 2018; Nakashima & Sugita, 2018). Furthermore, visual search experiments also suggested that the illusion occurs at a pre-attentive level (Busch & Müller, 2004): when the observer was asked to look for the largest circle, visual search time was faster when circles were surrounded by small inducers (in an Ebbinghaus-like configuration) than when no inducers were presented (control condition). This effect of context on search time was not modulated by the number of Ebbinghaus configurations on the display, which is a hallmark of parallel and pre-attentive processing (Treisman & Gelade, 1980).

The neural locus of the Ebbinghaus illusion

Psychophysical studies have taken advantage of the well-known functional organization of the visual system to infer the cortical locus of perceptual illusions (e.g., Cheng et al., 2018; Nakashima & Sugita, 2018; Song et al., 2011). Early structures as the retina, subcortical visual regions as the lateral geniculate nucleus, *LGN*, and the primary occipital or primary visual area, *V1*, have a large proportion of monocular neurons. In visual cortices beyond V1 and in high-level visual areas such as the lateral occipital complex, *LOC*, and the ventral occipitotemporal cortex, *vOT*, almost all neurons are binocular (Hubel & Wiesel, 1962; 1968). Therefore, by using *dichoptic* presentation, it is possible to examine whether the perceived size of the target presented to one eye is influenced by inducers presented to the other eye. Such *interocular* effects would suggest the involvement of binocular neurons at V1 or higher visual areas. In line with an early neural locus, the Ebbinghaus illusion is severely reduced in dichoptic relative to *monocular* presentation (i.e., target plus inducers presented to the same eye). In contrast, the Ponzo illusion (Ponzo, 1911; two parallel bars of equal size appear to be of different length when framed by two convergent lines) was as robust in monocular as in dichoptic presentation (Song et al., 2011) and did not survive CFS (Cheng et al., 2018; Nakashima & Sugita, 2018). Whereas the Ponzo illusion is thus mediated by binocular neuronal populations and possibly occurs at later stages of processing, the Ebbinghaus illusion occurs early on, being mediated by monocular neurons at V1 (or even earlier in the geniculostriate pathway).

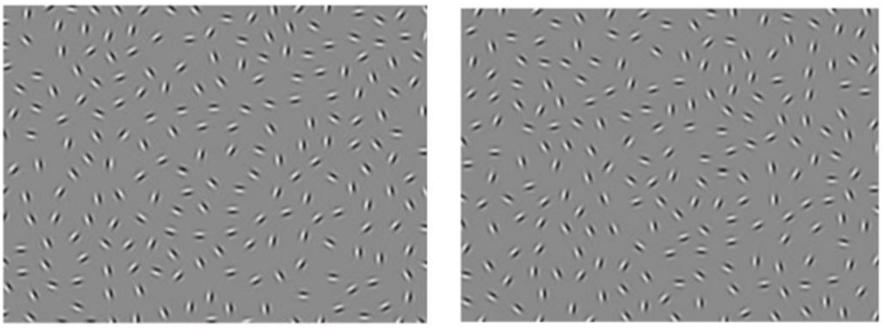
In sum, the available behavioral evidence suggests that the Ebbinghaus illusion is mainly dependent on interactions between contours. At the brain level, the loci seems to be the plexus of horizontal connections within V1 (Kaldy & Kovács, 2003; Schwarzkopf & Rees, 2013; Schwarzkopf, Song & Rees, 2011). Neuroimaging evidence suggests the involvement of early cortical regions, and specifically V1, in perceived rather than in physically-veridical (retinal) size (e.g., Sperandio, Chouinard & Goodale., 2012) and in the Ebbinghaus illusion (e.g., Schwarzkopf & Rees, 2013). Indeed, the strength of the Ebbinghaus illusion correlates with the size of V1; the illusion is stronger in observers with smaller central V1 surface area (Schwarzkopf, 2015; Schwarzkopf & Rees, 2013; Schwarzkopf et al., 2011). This agrees with the contour interaction account given that, in smaller V1 regions, the distance between neural representations of contours would be smaller, and hence, connections within V1 would be more efficient at inducing the Ebbinghaus illusion, compared to larger V1 regions. Importantly, V1 activation does mediate the Ebbinghaus illusion, and not objective size discrimination, given that the perception of size in a control condition with targets presented *without inducers* was not associated with V1 central surface area (Schwarzkopf & Rees, 2013).

Horizontal connections within V1 and contour integration

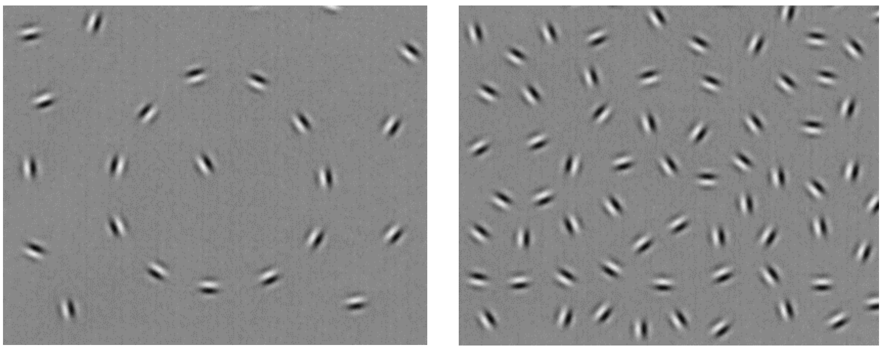
Kovács (2000) and Kaldy and Kovács (2003) proposed that horizontal cortical long-range interactions in V1 are the ones mediating contextual effects in the Ebbinghaus illusion. The strength of these connections has been measured with a *contour integration* task (Gervan & Kovács, 2010; Hadad, Maurer & Lewis, 2010), in which participants are presented with displays like those in Figure 3 with a closed chain of collinearly aligned Gabor signals (contour) and a background of randomly oriented and positioned Gabor signals (noise) and asked to detect the contour among noise. This contour cannot be detected purely by local filters nor by neurons with large receptive fields of the size of the contour; it can only be detected on the basis of long-range interactions, like horizontal cortical long-range connections in V1 that link cells with similar tuning preferences (Hadad et al., 2010; Kovács, Kozma, Fehér & Benedek, 1999).

Figure 3. Examples of material used in contour integration tasks (varying task difficulty)

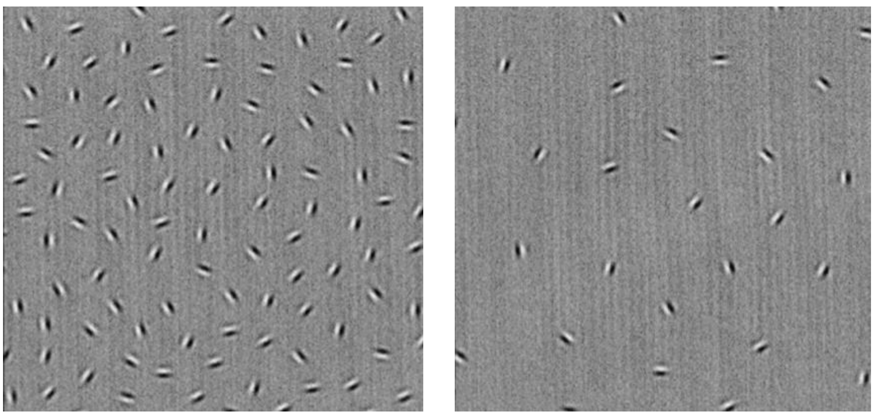
(A) *Varying the orientation of the contour elements*



(B) *Varying the noise density on the display*



(C) *Varying the contour spacing between elements*



Note. The left-side images present contours that are easier to detect than those in the right-side images.

The direct link between the contour interaction task and the horizontal connections within V1 was demonstrated by Li, Piëch, and Gilbert (2006; see also, van Kerkoerle, Marik, Borgloh, & Gilbert, 2018). The strength of these connections within V1 can be measured by manipulating task difficulty, either through jittering of the orientation of Gabor signals that make up the contour (Figure 3A) or by varying the relative noise density (Figure 3B), that is, the ratio in spacing between average noise and contour (Gervan & Kovács, 2010; Hadad et al., 2010). The length of these V1 connections can also be measured by augmenting spacing between Gabor signals that make up the contour (Kovács et al., 1999), as shown in Figure 3C.

Using this behavioral task, it has been suggested that horizontal connections within V1 have a protracted development until as late as 14 years of age (Hadad et al., 2010; Kovács et al., 1999). For example, Kovács et al. (1999; Experiment 1) manipulated the relative noise density in the display (while keeping contour spacing constant) in order to measure the strength of horizontal connections across development from five to 14 years of age and showed that contour detection increased along development, with the largest improvement between five to seven years old. The length of long-range interactions might also be limited in 5-6-year-old children, for whom contour integration was affected by spacing among contour elements but not for adults (Kovács et al., 1999; Experiment 2).

The V1 long-range interactions, underpinning contour integration, also seem to mediate the contextual effects in the Ebbinghaus illusion (Kaldy & Kovács, 2003; Kovács, 2000). Therefore, younger children would be less susceptible to the Ebbinghaus illusion than older children or adults. Given the developmental trajectory found for contour integration (Kaldy & Kovács, 2003; Kovács et al., 1999; Hadad et al., 2010), the largest developmental differences in the Ebbinghaus illusion would occur between five to seven years old.

The developmental trajectory of the Ebbinghaus illusion: is it really about maturation?

Most developmental studies have suggested that the largest developmental difference on the Ebbinghaus illusion occurs around seven years of age. Only Hanisch, Konczak, and Dohle (2001) suggested no differences in the Ebbinghaus illusion between five- and twelve year-olds and adults. However, these authors employed a "yes/no" paradigm that is sensitive to criterion changes across trials, conditions, or participants (Doherty et al., 2010; Hadad, 2018).

Most studies have adopted more stringent designs, with tasks more resistant to criterion changes as the two-alternative forced choice task (e.g., which inner circle is larger; Doherty et al., 2010) or the size adjustment task (i.e., participants adjust the size of an isolated comparison circle until they reach what they believe to be the same size as the one of the inner target circle surrounded by inducers; Hadad, 2018, Experiment 1), and with an additional condition with *no inducers* (e.g., Doherty et al., 2010) in order to ensure that any difference between age groups is not mere consequence of differences in size discrimination ability. These studies have systematically found a pattern of results compatible with the developmental differences reported for contour integration (Kovács et al., 1999). More specific, four-year-old children were less affected by the Ebbinghaus illusion, and hence, more accurate than adults (Hadad, 2018, Experiment 2; Kaldy & Kovács, 2003). The magnitude of the illusion seems to increase from 4 to 12 years of age, with the biggest differences occurring between 4-5 and 6-7 years of age (Hadad, 2018, Experiment 1; Imada, Carlson & Itakura, 2013; Weintraub, 1979; Zannuttini, 1996). Only Doherty et al. (2010) found no Ebbinghaus illusion before six years of age, after which the magnitude of this illusion increased.

Doherty et al. (2010) examined the Ebbinghaus illusion in 4-10 year old children and adults, while controlling the distance between the inner contours of smaller and larger inducers. This control was not usually done in previous studies and corresponds to a farther distance than the one often adopted with small inducers (e.g., Kaldy & Kovács, 2003; Schwarzkopf & Rees, 2013; Shaqiri et al., 2018). In fact, the design of Doherty et al. (2010) was quite controlled. A two-alternative forced-choice task was adopted on which participants decided whether the left or the right-side orange circle on the screen was the larger one. These circles always differed in physical size, from 2 to 18%, in steps of 4%.

Three types of display were used. In two, the orange circles were surrounded by gray circles, and hence, were presented *with inducers*, which, in turn, were always the largest and the smallest circles in the display (as in Doherty et al., 2008, and Phillips et al., 2004). In the third, control display, the orange circles were presented *without inducers*, which allowed assessing fine visual size discrimination without any influence of context. In the block with inducers, the orange target circles were surrounded by inducers with either *congruent* size, that is, the larger orange circle surrounded by the largest gray inducers in every size difference step (in 80 trials), or *incongruent* size, that is, the smallest orange circle surrounded by the largest gray inducers, which only occurred in the 2% size difference (in 8 trials).

Note that, the condition with congruent inducers represents the classical Ebbinghaus illusion: the effect of context is *misleading*, given that the physically larger inner circle surrounded by large inducers would be underestimated and the physically smaller inner circle surrounded by small inducers would be overestimated. In contrast, incongruent inducers would assist on (veridical) size discrimination, and hence, the context would be *helpful*, given that the larger target surrounded by the smallest inducers would be overestimated. This latter condition can provide further evidence on sensitivity to contextual effects.

Doherty et al. (2010) showed that the youngest groups at test (4 and 5-year-olds) were not affected by context on size discrimination; they were overall as accurate on size discrimination with congruent as without inducers. In fact, preschoolers had the best accuracy in the congruent condition (on average, above 75% in contrast to the 46% accuracy of adults). From age six onwards, observers were caught by the Ebbinghaus illusion, with worse performance with congruent than without inducers. The magnitude of the illusion (comparison between congruent inducers and no-inducers) increased along development. Across groups, it was larger when the real-size difference between the to-be-compared circles was smaller, suggesting that with large size differences the misleading effects of congruent inducers were overcome, as previously reported for adults (e.g., de Fockert et al., 2007; Doherty et al., 2008; Phillips et al., 2004). Note, however, that in the 2% size difference with incongruent (helpful) inducers, the youngest children showed the worst performance. Doherty et al. (2010) acknowledged that accuracy in this condition: "for adults it was then already at ceiling, but for 4- to 6-year-olds it was near chance" (p. 717), but also claimed that the overall pattern of results suggests that younger children are less affected by context.

From these results, the near chance performance of young children could be due to difficulties in discrimination of very small, 2% real-size difference. More important, congruent inducers are only deleterious for size discrimination if an observer is sensitive to context. However, besides immunity to context, other strategy could explain this pattern of results of the youngest children in such unbalanced design (eight trials of congruent inducers and only in the 2% size difference *vs.* 80 trials of incongruent inducers in all size difference steps at test). If young children were responding to the real size of the inducers rather than attending to the inner targets, then, when the large inducers surrounded the larger inner circle, they would be highly accurate. Such strategy would be misleading in the condition with incongruent inducers, where these children would perform at chance, just like the result reported. Indeed, children up to age six show a tendency to choose the inner circle surrounded by the larger inducers, regardless of the size of the inner circle (Thelen & Watt, 2010).

Furthermore, the Ebbinghaus illusion is sensitive to response strategies modulated by task instructions: encouraging the observers to ignore the inducers led to less illusion in adults (Doherty et al., 2008). This possibility could only be discarded with a balanced design, with the same proportion of trials with congruent and incongruent inducers (at all size differences). There, a strategy based on the size of inducers would no longer be effective, given that the larger target would be surrounded by small inducers in half of the trials, and hence, the overall performance would be at chance (close to 50%). In contrast, immunity to context would lead to above chance performance in this incongruent condition, and one close to that without inducers.

Doherty et al. (2010) also found a negative correlation between general nonverbal intelligence, measured by the *Colored Progressive Matrices of Raven* (CPM; Raven, 1965), and overall accuracy in size discrimination in 4-10-year-olds. Along age, a complex correlation pattern was found: for 4-year-olds only, this correlation was positive, but between 5 and 10 years old the correlation tended to be negative albeit non-significant. Doherty et al. (2010) suggested that this pattern of results reflects one of two possibilities: either the time spent looking at pictorial spaces (which, would play a role in the illusion) is positively correlated with intellectual abilities, or intellectual abilities require sensitivity to context. Neither explanation explains the asymmetric pattern observed for the 4 year olds relative to the other age groups. This correlation might reflect the role of cognitive development on context sensitivity or the role of another moderator variable like literacy (see Kolinsky, 2015).

Other studies have also shown that preschool children have smaller susceptibility to the Ebbinghaus illusion than older children or adults (e.g., Hadad, 2018; Kaldy & Kovács, 2003; Zannuttini, 1996; Weintraub, 1979). However, whether preschoolers are indeed immune to or just less influenced by context is still unclear. In fact, the Ebbinghaus illusion has already been reported in 5-8 month olds (Yamazaki, Otsuka, Kanazawa, & Yamaguchi, 2010) and in most studies it is already evident in four-year-olds, albeit much smaller than in adults, even in a following study using the same method and material as Doherty et al. (2010; Bremner et al., 2016). Regardless of disparities between developmental studies, their common denominator is that the largest difference in the Ebbinghaus illusion is found between preschool and school years (that is, between 4-5 vs. after 6 years of age; Bremner et al., 2016; Doherty et al., 2010; Hadad, 2018, Experiment 1; Zannuttini, 1996; Weintraub, 1979) in line with the developmental trajectory found in contour integration (Kovács et al., 1999).

Note, however, that these so-called developmental differences between preschool and school years could rather depend on experience-based perceptual learning, regardless of age, instead of neural maturation. Indeed, long-range connections within V1 have been shown to be highly plastic and responsive to short-term learning (Gilbert et al., 1996; Kovács et al., 1999; Li & Gilbert, 2002; Li, Piëch & Gilbert, 2004; 2008; McManus et al., 2011; Schwarzkopf & Kourtzi, 2006). Even in adults, training on contour integration led to changes in the structure of axonal arbors in V1 (van Kerkoerle et al., 2018). Therefore, in the present thesis, we hypothesized that experience-dependent, perceptual training could be the basis of, or at least one strong factor for, the age effects previously found in the Ebbinghaus illusion. Specifically, we hypothesized that a cultural micro-level variable could be an important experience-dependent moderator on the Ebbinghaus illusion, not only between preschool and school years in children, but also between adults from different cultures.

The influence of culture at macro-level in the Ebbinghaus illusion

Different cultures have shown different patterns of sensitivity to visual contexts (e.g. Masuda & Nisbett, 2001; Varnum, Grossmann, Kitayama & Nisbett, 2010). In such studies, *culture* has been considered at macro level, that is, as the set of social norms, beliefs and knowledge shared by a group of people. Therefore, culture has been considered in a spectrum, from an *analytic* style of processing, that is, *context-independent*, where a part of a stimulus is not influenced by the other parts, to a *holistic* style of processing, that is, *context-dependent*, where the perception of a part is influenced by the other parts[4]. Two major theories have been proposed to explain such cultural differences in visual processing.

[4] Note, however, that the terms analytic and holistic have been loosely defined and used to describe cognitive styles in general, even outside the visual domain. In fact, it has been suggested that individuals from one culture (not groups) are not consistently more analytic or more holistic across different measures, which suggests that these terms are not really tapping into the same phenomenon in different tasks (Na et al., 2010).

Social orientation hypothesis

The *social orientation hypothesis* (e.g. Varnum et al., 2010) states that cultural differences on perception are attributed to the way those cultures endorse social interactions. Cultures that emphasize self-direction, autonomy and self-expression, that is, independent (or individualistic) cultures, such as Western, should also be more analytic in their perceptual habits, while cultures that emphasize harmony, relatedness and connection, that is, interdependent (or collectivist) cultures, such as East Asian, should be more holistic. The locus of this effect would be chronic differences in attention: independence focuses attention on objects; while interdependence prompts wide attention to context.

In accordance with this theory, there is evidence of a more holistic, context-dependent, processing among interdependent cultures, such as Central European and East Asian, compared to more independent ones, such as Western, on the *Framed Line Task* (FLT[5]): Participants from interdependent cultures are more accurate in the relative task (Varnum, Grossmann, Katunar, Nisbett & Kitayama, 2008; Kitayama, Duffy, Kawamura & Larsen, 2003). Along with those cross-cultural differences, differences in visual processing have also been found within-culture between groups that vary in social orientation, such as Hokkaido and Mainland Japanese (Kitayama, Ishii, Imada, Takemura & Ramaswamy, 2006), Working-class and Middle-class Americans (Na et al., 2010), and Farmers/Fishers and Herder communities in the Black Sea region of Turkey (Uskul, Kitayama & Nisbett, 2008).

Some prior studies on the Ebbinghaus illusion seem to agree (at least partially) with this proposal, given that East Asian observers showed greater sensitivity to context, and hence, larger Ebbinghaus illusion than Westerners (Doherty et al., 2008). However, this cultural difference has only been found after the age of six (Imada et al., 2013). Furthermore, contrary

[5] In the FLT, participants are presented with a square frame in which a line is drawn. They are then shown other square frames of various sizes and asked to draw a line that was identical to the first line in either absolute length (absolute task) or in ratio relative to the surrounding frame (relative task).

to this proposal, British adults show larger susceptibility to the Ebbinghaus illusion than Himba Namibian adults (Bremner et al., 2016; Caparos, Ahmed, Bremner, de Fockert, Linnell & Davidoff, 2011; Davidoff, Fonteneau & Goldstein, 2008; de Fockert et al., 2007), and this cannot be attributed to differences in iris pigmentation (Coren & Porac, 1978). Himba are "seminomadic people in a remote area of northen Namibia, who have extremely limited access to Western technology and no formal education" (de Fockert et al., 2007, p. 738) and interdependent social systems (Gluckman, 1965): They live in a social community structured around large family compounds where roles and behavior appear to be rigidly enforced. According to the social orientation hypothesis (Nisbett et al., 2003) and contrary to what has been observed (e.g., Caparos et al., 2011; Davidoff et al., 2007; de Fockert et al., 2007) Himba would be more holistic and hence more susceptible to the Ebbinghaus illusion than Westerners.

Physical environment hypothesis

The *physical environment hypothesis* (e.g. Miyamoto, Nisbett & Masuda, 2006; Nisbett & Miyamoto, 2005) states that cultural differences found in visual perception are largely dependent on perceptual environments. Cultures marked by cluttered environments with ambiguous objects promote holistic processing because focusing on details would be overstimulating, whereas cultures marked by uncluttered environments with salient objects promote analytic processing due to focusing on few salient details.

Indeed, in a *change blindness* task in which participants view two sequentially presented similar pictures or animated vignettes and have to detect slight changes made on focal or contextual elements, changes made to contextual elements were more detected when the picture or animated vignette was of a Japanese city (a cluttered environment) than when it was of an American city (a relatively less cluttered environment), regardless of cultural background. When the picture or animated vignette was of a culturally neutral scene, as construction sites, Japanese detected more changes to contextual elements than Americans, and Americans detected more changes to focal elements than Japanese (Miyamoto et al., 2006). Furthermore, showing that this cultural influence in visual perception might be rather dependent on attention, and flexible, when Japanese students were primed with pictures of American cities, they became more analytic than Japanese who were not primed when they were presented with the culturally neutral scenery, and vice-versa for American students primed with Japanese cities (Miyamoto et al., 2006). This suggests that chronic differences in cultural patterns of attention caused by the perceptual environment generalize to non-cultural scenes and objects.

It thus seems that more than philosophical or referential systems, the visual environment could be a critical factor for the supposedly-cultural differences in the Ebbinghaus illusion. For example, Jahoda and Stacey (1970) found that Ghanaian college students from less industrialized settings than Scottish students were less susceptible to the Ebbinghaus illusion. Note that Ghanaian observers came from coastal plains or the central forest belt, where there is a lot of open, uncluttered, space, whereas Scottish came from cities with cluttered environments. Caparos et al. (2011) showed that rather than the cultural referential system, the perceptual environment is responsible for differences in the Ebbinghaus illusion between Japanese, British and Himba observers. In order to test the visual clutter account, Himba observers varied on amount of exposition to urban environments: urban Himba lived in urban environments (on average, for six years); traditional Himba had reduced experience with urban environments (and also varied in number of visits to cities). Whereas Japanese observers were the most susceptible to the Ebbinghaus illusion, traditional Himba were the least susceptible. Interestingly, urban Himba did not differ from British observers. Note that a great deal of experience with cluttered environments seems necessary for modulation of visual processing, given that the number of times traditional Himba observers visited an urban environment was not correlated with the magnitude of the Ebbinghaus illusion (see also Bremner et al., 2016).

What is clear from the physical environment hypothesis (e.g. Miyamoto et al., 2006;

Nisbett & Miyamoto, 2005) is that experience-dependent influences, regardless of the macro societal frame, affect visual perception and specifically the Ebbinghaus illusion. More important, culture is not a cause but rather a moderator in the Ebbinghaus illusion. Indeed, regardless of culture, all observers were sensitive to the Ebbinghaus illusion (e.g., Himba vs UK adults: de Fockert et al., 2007; British and Japanese college students: Caparos et al., 2011; Doherty et al., 2008; Scottish and Ghanaian: Jahoda & Stacey, 1970).

Perceptual learning: the common mechanism

A critical aspect on the study of cultural differences is to understand the mechanism responsible for such cultural modulation of visual perception. In light of this, rather than dependent of culture in sensu stricto, visual processing could rather be influenced by *perceptual learning* (Gilbert & Li, 2012), i.e., extensive experience in perception of visual scenes or objects which leads to the adaptation of visual brain regions to these frequently encountered stimuli due to experience-dependent synaptic plasticity, regardless of such experiences being cultural or not (Gilbert & Li, 2012; Gilbert et al., 2001; Sagi, 2011; Sasaki et al., 2009). This results in more efficient and less effortful processing of these frequently experienced stimuli (Sigman, Pan, Yang, Stern, Silbersweig & Gilbert, 2005). In this vein, chronic differences in culture-specific patterns of attention would lead to a perceptual bias in visual perception which would have occurred due to perceptual learning.

This hints that the cultural differences in the Ebbinghaus illusion might not be due to culture at a macro-level, and the developmental differences might not be due to maturational development. Instead, we suggest that it could be that micro-level cultural variables would influence even the early visual processing levels that underpin the Ebbinghaus illusion (Cheng et al., 2018; Song et al., 2011) as consequence of experience-dependent perceptual learning.

We are not the first to propose the importance of perceptual learning in the modulation of the Ebbinghaus illusion. In fact, although not explicitly stated, the physical environment hypothesis (e.g. Miyamoto et al., 2006; Nisbett & Miyamoto, 2005) is one about perceptual learning (see also e.g., Caparos et al., 2011; de Fockert et al., 2007). Furthermore, Doherty et al. (2010; Bremner et al., 2016) suggested that the engagement with pictorial stimuli and print could explain the developmental trajectories and cross-cultural differences in the Ebbinghaus illusion, given that the ability to compute depth and size of 3D objects represented in 2D pictures would require perceptual training and exposure to such pictures. Therefore, observers with less experience with such pictorial information would also be less susceptible to the Ebbinghaus illusion, as happens in young children and in adults from remote cultures.

Taking this into account, Bremner et al. (2016) examined the Ebbinghaus illusion in Himba and British observers from three years of age until adulthood. Across age, from 3-10 years old, Himba observers had lower size discrimination abilities than British observers (and this hold true even when no inducers were presented). Three to six year-old children showed the smallest illusion (computed as the difference in accuracy between the condition of congruent inducers and no-inducers), regardless of culture. It was only after age 7, that cultural differences were observed (as previously found with Japanese vs. American children; Imada et al., 2013): Himba children from rural environments were overall the least susceptible to the Ebbinghaus illusion, and British were the most susceptible, while the Urban Namibians were in between. Regardless of age, rural Himba were the observers with the smallest, albeit reliable, illusion, even when compared with urban Himba. Interestingly, 3-5-year old Himba children from urban environments showed a significant (albeit small) Ebbinghaus illusion and were more accurate in a helpful context (incongruent inducers) relative to no-context (no inducers), questioning the possible immunity of young preschool children to contextual information and to the Ebbinghaus illusion (Doherty et al., 2010). Differences in visual clutter of the landscape were not the main factor underlying cultural differences, given that no significant correlation was found between the magnitude of the Ebbinghaus illusion and exposure to the urban environment (Experiment 3). More important, number of years of schooling was significantly correlated with the magnitude of illusion, and this held true even after controlling for years of exposure to urban environment and age.

As a matter of fact, in all studies, Himba adults with disperse schooling (from 0 to 12 years of education) were compared to Western urban college students or academics (with at least 12 years of education), and hence, besides cultural referential, the two groups did differ in schooling, an experience-dependent factor known to influence perceptual processes (e.g., Myamoto et al., 2006; Ventura, Pattamadilok, Fernandes, Morais, & Kolinsky, 2008) and possibly the Ebbinghaus illusion (Bremner et al., 2016). Yet, besides schooling, another cultural object could be responsible for these results. Indeed, for most *WEIRD* (Western, educated, industrialized, rich, democratic) people (cf. Henrich, Heine, & Norenzayan, 2010), learning to read starts at school entrance. More important, it is possible do disentangle the influence of reading from that of schooling.

Previous studies have shown that, regardless of schooling, learning to read can have deep consequences in visual processing. The strongest evidence comes from cross-sectional studies that examined three groups of adults matched in age, from the same cultural and socioeconomic milieu, but who differed in schooling and literacy: unschooled *illiterate* adults, who did not attend school nor learned to read and write but have no neurocognitive deficit that would have precluded literacy acquisition; unschooled *ex-illiterate*, who learned to read in adulthood; and schooled *literate* (e.g. Dehaene et al., 2010; Kolinsky et al., 2011; Szwed et al., 2012). Recruiting ex-illiterate adults allows researchers to distinguish between literacy and schooling effects, given that they learned to read but outside school.

Learning to read and the Ebbinghaus illusion

Learning to read is a gateway to culture and education and has so deep impact in the organization of the brain and mind that it goes beyond the emergence of a reading specialized circuitry, with the so called *Visual Word Form Area,* VWFA, at its heart (Dehaene & Cohen, 2011; Dehaene et al., 2010; Dehaene-Lambertz, Monzalvo, & Dehaene, 2018). It also affects evolutionary older neurocognitive systems like visual object recognition (for a review, see, Dehaene et al., 2015). Indeed, the emergence of the reading circuitry shapes the ventral, vision-for-perception, stream dedicated to visual object recognition (Goodale & Milner, 1992), from early, low-level, primary visual regions, V1, to high-level visual regions of the ventral occipitotemporal cortex, vOT. For example, using functional magnetic imaging, fMRI, Szwed et al. (2011) showed that functional activation at V1 is larger for words than for well-matched scrambled control items, which suggests that extensive experience with print, probably due to this intensive perceptual training, leads to adaptation of V1 to the shapes that compose letters (Chang et al., 2015; Szwed et al., 2011; Szwed, Qiao, Jobert, Dehaene & Cohen, 2014).

According to the *Neuronal Recycling Hypothesis* (Dehaene, 2009), vOT regions were partially recycled to accommodate literacy, with spillover effects on the evolutionary-older function. Indeed, the impact of literacy can be found in several visual tasks outside the written domain (see Kolinsky, 2015) and there is considerable evidence to suggest that literacy, as opposed to schooling in general, plays a role in the susceptibility to the Ebbinghaus illusion.

Cross-sectional studies with unschooled illiterate, ex-illiterate, and schooled literate adults have shown that learning to read enhances early visual responses in the occipital cortex, including in V1, to visual stimuli, not only to letter strings but also to nonlinguistic stimuli as horizontal checkerboards, faces, and pictures of objects (Dehaene et al., 2010). Similarly, event-related potential (ERP) responses evoked at the 140-180 ms time-window to visual stimuli were also enhanced in readers (ex-illiterate and literate) relative to non-readers, as well as repetition suppression (that is, reduction of ERP amplitude in response to the second repeated stimuli relative to two different stimuli) at 100-150 ms (Pegado et al., 2014). Given that repetition suppression reflects the brain's capacity to discriminate two items (e.g. Nemrodov, Jacques, & Rossion, 2015; Vizioli, Rousselet, & Caldara, 2010), these results suggest that literacy facilitates fast discrimination of similar-looking stimuli. Second, providing direct psychophysical evidence for the role of learning to read in contour integration, Szwed et al. (2012) showed, using a visual integration task (see Figure 3), that visual integration was enhanced in readers, regardless of schooling, as ex-illiterate and schooled literate adults were better than illiterate in connecting local elements into an overall shape. No significant difference was found between schooled and unschooled readers, so it was learning to read that enhanced contour integration.

The present study

In the present thesis, we hypothesized that learning to read would enhance the magnitude of the Ebbinghaus illusion. The rational is that horizontal connections at V1 are the neural underpinning of contour integration (Li et al., 2006; van Kerkoerle et al., 2018), which are also proposed to mediate the contextual effects in the Ebbinghaus illusion (Kaldy & Kovács, 2003; Schwarzkopf & Rees, 2013), and learning to read was already shown to enhance V1 functioning (Dehaene et al., 2010) and contour integration (Swed et al., 2012).

To control for maturation confounds, this hypothesis was examined in two experiments, one with adults, the other with children, with a design similar to that of Doherty et al. (2010), except that we adopted a balanced design, with the same number of trials in each size difference between the two critical circles (from 2 to 18%) in the three contexts (i.e., congruent and incongruent inducers in the block with inducers; no-inducers in the block without inducers) and all material was black to ensure that differences in lightness/color between target and inducers would not be involved (see Bremner et al., 2016),

In Experiment 1, observers were unschooled illiterate, ex-illiterate, and schooled literate adults, matched in age and sex and from the same socioeconomic and cultural background. In Experiment 2, observers were two groups of children matched in age and cognitive development, who differed only in schooling/literacy: pre-literate preschoolers vs. first-grade readers. Providing convergent evidence in these two experiments would allow to robustly test whether learning to read was indeed the main responsible for differences in susceptibility to the Ebbinghaus illusion. Also, the comparison of the magnitude of the illusion between adults and children allowed to examine whether neural development would indeed have any influence in the magnitude of the illusion.

Based on our hypothesis, in both experiments, non-readers (Experiment 1, illiterate adults; Experiment 2, pre-literate children) would be less susceptible to context in size discrimination than readers (Experiment 1, ex-illiterate and literate adults; Experiment 2, beginning readers at the 1st-grade), albeit as able as readers to perform veridical size discrimination (without inducers). We thus expected a significant two-way interaction between group and context. To put it differently, illiterate (and pre-literate) would be less susceptible to the classical Ebbinghaus illusion, and hence, more accurate than readers in size discrimination of a target surrounded by congruent inducers. Likewise, denoting the smaller influence of context for non-readers, they would be less accurate than readers in size estimation for targets surrounded by incongruent inducers. Given that adults might reach accuracy at ceiling when size differences are large, hence, leaving no room for influences of context, the three way interaction between group, context, and size difference would also be significant in Experiment 1. Thus, the influence of literacy would be stronger for smaller than larger size differences (Bremner et al., 2016; Doherty et al., 2010; Philips, Chapman & Berry, 2004).

Furthermore, we also examined the association between working memory and the magnitude of the illusion at the individual level, given prior evidence (Coren & Porac, 1987; Doherty et al., 2010; de Fockert & Wu, 2009).

Experiment 1

Method

This and Experiment 2 were approved by the Deontological Committee of Faculdade de Psicologia, Universidade de Lisboa, and followed the international guidelines, including Declaration of Helsinki, and the Portuguese regulation for ethics in research in Psychology.

Participants

Fifty Portuguese adults from the same socioeconomic, cultural, and residential backgrounds were paid and participated voluntarily after they gave informed consent. They were recruited with the help of non-governmental agencies. According to literacy/schooling, participants were assigned to three groups, matched in sex, $H(2, N = 50) = 3.56$, $p = .17$, age, $F < 1$, and in general cognitive profile ($F < 1$, *MMSE*[6]; Portuguese version: Guerreiro et al., 1994): 21 illiterate (2 men; *M*age = 38.4 yrs, *SD* = 7.2), who were either not attending to or were at the first two weeks of alphabetization courses, before reading instruction starts; 14 unschooled ex-illiterate (5 men; *M*age = 40.9 yrs, *SD* = 11.5), who had already finished the alphabetization course and had automatic reading skills (see below); 15 schooled literate (4 men; *M*age = 38.6, *SD* = 12.8).

Materials and Procedure

Before the experimental task, participants performed ancillary tests (see Table 1).

Ancillary tests.

Literacy indexes. Four tests ensured that illiterate adults had no reading skills but they did vary on letter knowledge. More important, these indexes allowed examination, at the individual level, of whether and how literacy associates with susceptibility to the Ebbinghaus illusion (in the experimental task).

Participants were tested on *letter naming* of 23 upper-case and 23 lower-case letters of

[6] The MMSE is sensitive to educational/literacy levels (e.g. Crum, Anthony, Bassett & Folstein, 1993). Thus, we used revised scores, discarding the items examining reading, writing, and arithmetic abilities.

the Latin alphabet (excluding *k*, *y*, and *w*) presented sequentially in a fixed order, differing from the one in the alphabet. The *offline reading task* comprised three lists of items (5 high-frequency words; 15 low-frequency words; 15 pseudowords), which participants read aloud without time pressure. *Reading fluency* was assessed with the reading fluency subtest of the *Differential Diagnosis Dyslexia Maastricht Battery* (*3DM* Battery, Portuguese Version; Reis et al., in preparation) and examined whether ex-illiterate and literate had automatic reading skills. In this test, participants read aloud as fast and accurate as possible a list of items presented on the computer screen in 30 s (per list): high-frequency words; low-frequency words; and pseudowords (fixed-order). *Reading comprehension* was assessed with the *Teste de Idade de Leitura*, *TIL* (Sucena & Castro, 2008). This is a paper-and-pencil test that examines sentence comprehension. Participates are presented with 36 incomplete sentences (arranged in two A5 sheets, each with 18 sentences) and asked to select which of five words presented in parenthesis correctly completes each sentence, within 5 min.

As shown in Table 1, illiterate adults varied on letter knowledge (from 0 to 28 letters correctly named) and had lower letter knowledge than ex-illiterate and literate adults (Bonferroni: both ps < .001). The two latter groups did not differ significantly from each other ($p = .77$). In the literacy index, computed as the summed score across all literacy measures (i.e., letter naming, offline reading, 3DM, and TIL-5 min), the three groups differed significantly, $F(2, 47) = 248.00$, $p < .001$; literate had the highest score (both ps < .001). Ex-illiterate adults followed in-between, with higher literacy scores than illiterate ($p < .001$), as shown in Table 1.

Working memory. Participants were examined in visuospatial working memory with the *Corsi block* test (Wechsler Memory Scale, 3rd ed.; Wechsler, 1997), and in verbal (phonological) working memory with the Digit Span test (Wechsler Adult Intelligence Scale, 3rd ed.; WAIS-III; Portuguese version: Wechsler, 2008).

Table 1

Average performance by the three groups in the ancillary tests

	Illiterate (n = 21)	Ex-illiterate (n = 14)	Literate (n = 15)
MMSE	21.86 (3.32)	27.71 (1.73)	27.73 (1.75)
Letter Naming	14.00 (10.35)	44.64 (1.28)	45.40 (0.99)
Reading Performance:			
Offline Reading – high frequency words	0.33 (1.53)	15.00 (0)	14.87 (0.35)
Offline Reading – low frequency words	0.24 (1.09)	14.36 (1.00)	14.33 (1.50)
Offline Reading - pseudowords	0.14 (0.65)	14.36 (0.84)	14.33 (1.05)
3DM[a] – high frequency words	0	24.21 (9.96)	40.33 (12.26)
3DM – low frequency words	0	16.64 (8.58)	33.13 (13.14)
3DM – pseudowords	0	15.71 (6.21)	22.87 (7.39)
TIL-5 min	0	13.07 (6.34)	21.93 (7.06)
Literacy Index[b]	14.71 (11.78)	158.00 (29.52)	207.20 (38.18)
Working memory:			
Visuospatial working memory: Corsi blocks	8.19 (1.54)	10.79 (2.61)	11.13 (3.00)
Verbal working memory: Digit Span	6.81 (1.97)	10.00 (1.88)	9.87 (2.61)

Note. SD in parenthesis; mean performance in all tests was computed using raw scores.

[a] Reading fluency: Total items read correctly in 30 s.

[b] Summed score across all literacy measures (i.e., letter naming, offline reading, 3DM, and *TIL*-5 min)

The digit span subtest comprises two blocks. In the first block, participants are asked to repeat the sequence of digits produced by the experimenter (direct order); in the second block, they are asked to produce the sequence in inverse order (from the last to the first digit produced by the experimenter). It comprises 16 series of digits (from two to eight) in the direct block and 14 series in the inverse block. The test ends after two consecutive errors or after the participant reaches the end of the sequences.

The Corsi blocks test is a 3D visuospatial version of the former test: a 9-cube board is presented and participants are asked to tap each cube in the correct order following the order produced by the experimenter. In the first block, the participant must produce the sequence in the direct (same) order as the experimenter; in the second block the participant must produce the sequence in the reverse order (from the last to the first cube tapped by the experimenter). Sequences start with a span of two cubes until eight cubes. After participant reaches the final sequence (16 in total, the last with eight steps) or after two consecutive errors the block ended. In both tests, performance was computed as the number of sequences correctly performed in total (in the two blocks). After the ancillary tests, participants did the experimental task.

Experimental material and procedure.

Three types of black circles, on a white background, were prepared with *Power point* (Microsoft): *small* and *large inducers* with diameters of 50 and 125 pixels, respectively; one *reference* circle with 100 pixels; ten *comparison circles* with sizes from 82 to 118 pixels in steps of 4 pixels.

As illustrated in Figure 4, in the block *without inducers,* in each display, the reference and one of the comparison circles were presented at the same distance of ~4.92º from the center of the screen, and at the center of each one of the two 3x3 matrixes, leading to 10 different displays, resulting from the orthogonal manipulation of *size difference* (in %) between the reference and comparison circle (within-participants variable: 2, 6, 10, 14, 16) and whether the reference circle was smaller or larger than the reference circle. For each of these 10 displays, two versions were created (20 displays in total): in one the reference circle was on the left side, in the other it was on the right.

In the block *with inducers*, in each display, the two circles (reference and comparison) were surrounded by eight inducer circles each, whose inner contour was at the same distance of the contour of the inner circle regardless of inducers' size (0.40º). For each of the 20 displays, two versions were created, by manipulating *size congruency* of the inducers and the inner circle. As shown in Figure 4, in the *congruent* (*size*) condition, the larger inner circle was surrounded by the largest inducers; in the *incongruent* condition, the larger inner circle was surrounded by the smallest inducers. These two conditions occurred equally often in the block with inducers and in randomized order.

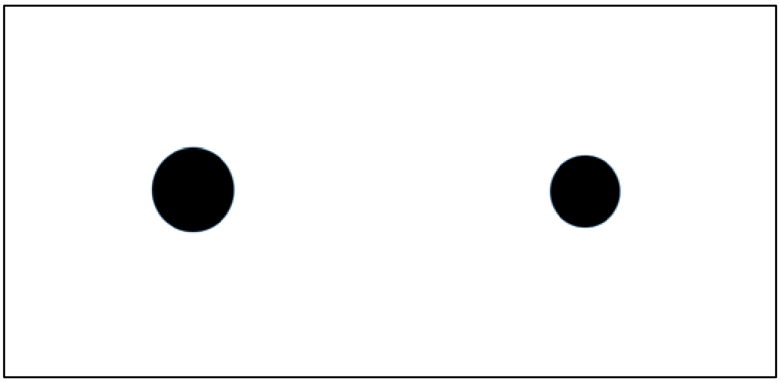
Participants performed a size judgment task, through key presses, deciding which circle was the larger (the one from the left or from the right) in the two blocks (with or without inducers) of computerized trials in a fixed order: block with inducers first.

Before each block, participants were presented with two demonstrations in paper. Before the block with inducers, each demonstration comprised two inner black circles (one on the left, the other on the right) surrounded by eight circles each. Participants were asked to decide which of the two inner circles was the larger, by pointing. They were told that they should ignore the surrounding circles as these were irrelevant to the task. Next, they performed the computerized trials.

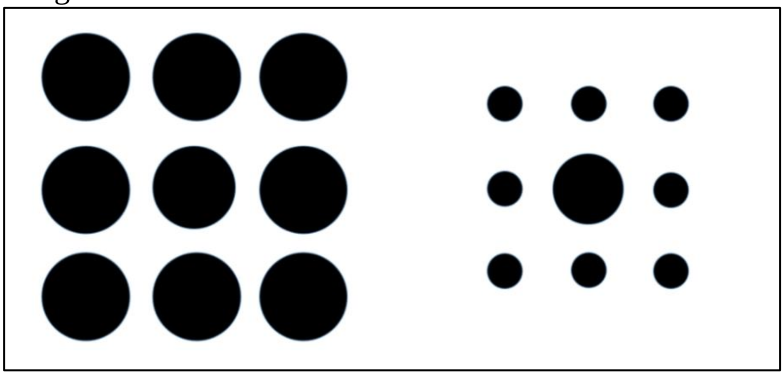
Stimulus presentation, the sequence of events, and data collection were controlled by *E-Prime 2.0* (http://www.pstnet.com/eprime) in a laptop computer with a 21.5 × 38.3 cm screen (resolution: 1600 × 1024 pixels; 60 Hz refresh rate). Participants were seated at a distance of ~ 80 cm from the screen (without head fixation). In the first block, with inducers, participants were presented with 12 practice trials followed by the experimental trials. Sequence of events is presented in Figure 5 and was the same in practice and experimental trials, with the only difference that participants received feedback on their performance only in the former trials.

Figure 4. *Examples of the displays in the three conditions (i.e. no context; congruent; incongruent)*

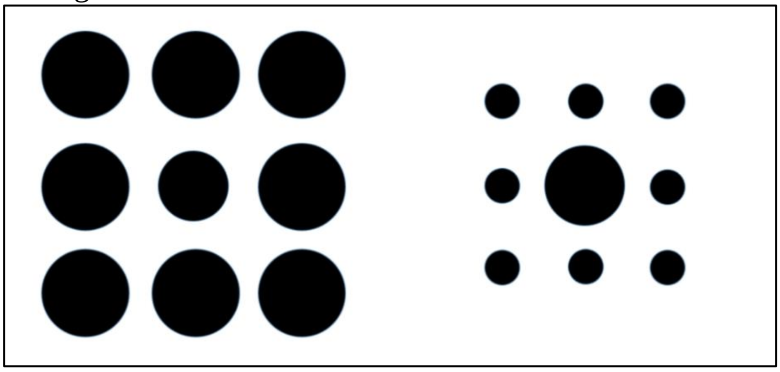
No context



Congruent



Incongruent

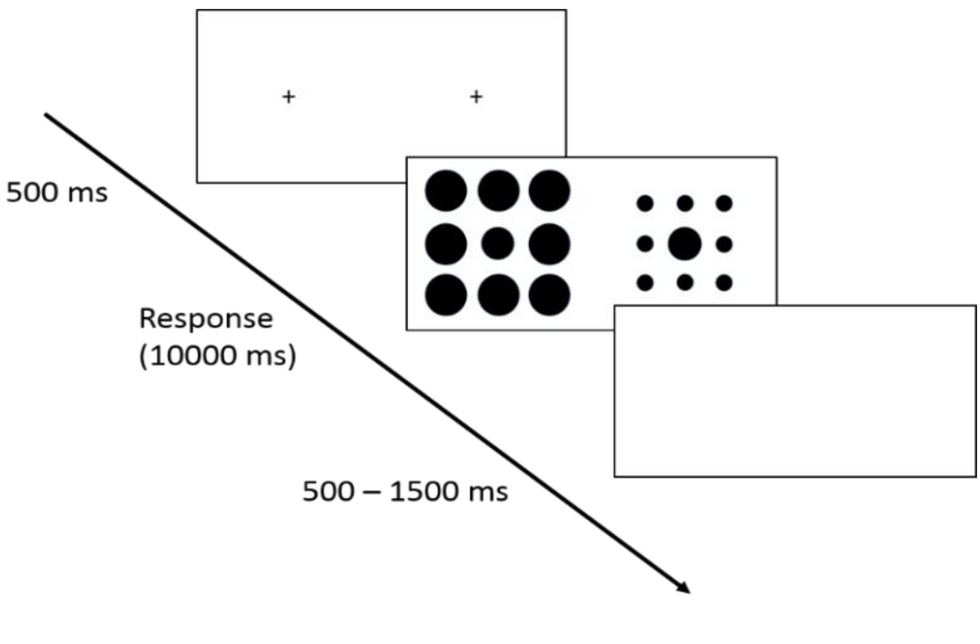


Note. Congruent and Incongruent were presented in a block with inducers.

In each trial, two fixation crosses were presented on a white background for 500 ms, at the location where each inner circle was presented next for 10 s or until response, whatever came first. Participants were asked to decide which circle was larger: the left circle, by pressing the "1" key with the left index-finger; or the right circle, by pressing the "2" key with the right index finger. After response (or 10 s), a white screen appeared during a jittered time of 500 to 1500 ms (in steps of 250 ms), after which the next trial began. Participants performed 160 trials in the block with inducers: 16 in each size congruency (congruent vs. incongruent) x step of the size difference between reference and comparison circle (2, 6, 10, 14, 18).

In the second block, demonstration, practice, and experimental trials, as well as sequence and duration of events in each computerized trial were equivalent to the first block, except that participants were presented with two (inner) circles without inducers. After six practice trials (with feedback on response), participants performed 80 experimental trials (each display appeared four times with order randomized: 4 x 20 displays).

Figure 5. *Sequence of events in experimental trials*



Results and Discussion

For the sake of consistency with previous studies adopting the same experimental task (e.g. Bremner et al., 2016; Doherty et al., 2008; Doherty et al., 2010; Philips et al., 2004), all analyses were run on accuracy (i.e., proportion of correct responses) instead of considering psychometric functions. Accuracy was analyzed using the raw scores of the proportion of correct responses but for the sake of clarity the results are presented here in percentages.

We ran a mixed ANOVA on accuracy with group (illiterate; ex-illiterate; literate) as a between-participants variable, context (no context; congruent; incongruent) and size difference (in %: 2; 6; 10; 14; 18) as within-participants variables.

The main effect of size difference was significant, $F(4, 188) = 530.44$, ηp2 = .92, $p < .001$, and was not modulated by group, $F(8, 188) = 1.37$, $p = .21$. As expected, the smaller the size difference between the reference and the comparison circles, the harder size judgments were. The main effect of context was also significant, $F(2,94) = 369.82$, $\eta p^2 = .89$, $p < .001$, denoting participants' overall sensitivity to the surrounding information and also revealing an Ebbinghaus illusion. Specifically, participants had significantly worse performance in the incongruent than in the no-context condition, $F(1, 47) = 338.18$, $p < .001$, and better performance in the congruent than in the no-context condition, $F(1, 47) = 105.83$; $p < .001$.

Table 2
Mean accuracy (in %) of the three groups in each context

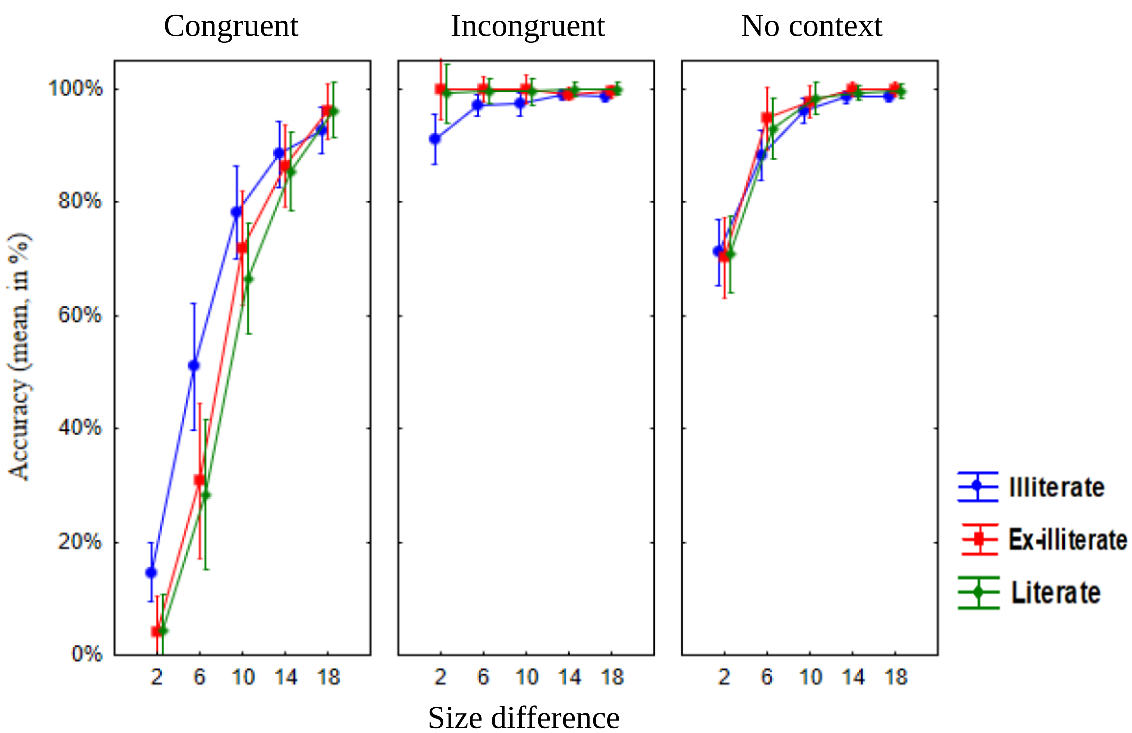
	Illiterate	Ex-illiterate	Literate	Across- Groups
No context	90.62 (7.11)	92.57 (4.11)	92.24 (3.51)	91.65 (5.42)
Congruent	64.99 (11.70)	57.87 (12.69)	56.27 (12.73)	60.38 (12.69)
Incongruent	96.72 (4.90)	99.74 (0.51)	99.68 (0.71)	98.46 (3.49)

Note. SD in parenthesis.

The three groups did differ in sensitivity to the surrounding context, but not on veridical size judgments or visual acuity. This was revealed by a significant Group x Context interaction, $F(4, 188) = 3.90$, ηp2 = .14, $p < .01$ (main effect of Group, $F < 1$), as shown in Table 2.

More important, and revealing that the influence of learning to read is really about sensitivity to context and not size processing per se, the three-way interaction between group, context, and size difference was significant, $F(16, 752) = 3.47$, ηp2 = .13, $p < .001$ (Step x Context, $F(8, 376) = 207.61$, ηp2 = .82, $p < .001$). As we expected, the influence of context, including the Ebbinghaus illusion (influence of congruent context), was stronger in smaller size differences than in larger ones (e.g., Bremner et al., 2016; Doherty et al., 2010), where the influence of literacy could be better appreciated. In other words, the difference in performance between no context and the two context conditions (incongruent and congruent) was larger for the smallest size differences, where performance was not at ceiling, thus leaving room for the observation of contextual effects and the modulation by literacy.

Figure 6. *Accuracy by size difference in each condition for the three groups*



Note. Error bars represent the SEM - standard error of the mean.

As show in Figure 6, in no context, there was no effect of group, $F(2, 47) = 0.66$, nor any interaction with size difference, $F = .86$. All groups behave similarly, with equivalent slopes in performance along size difference steps.

In the congruent context, the interaction between group and step was significant, $F(8, 188) = 3.37$, $p = .001$, $MSE = 4.198$, because illiterate adults were more accurate than either ex-illiterate or literate adults in the hardest size difference conditions, that is, in the two smallest differences of 2% (Step 1), $F(1, 47) = 6.53$; $p = .014$, g[7] = .79, and $F(1,47) = 6.092$, $p = .017$, $g = .73$, respectively, and 6% (Step 2), $F(1,47) = 5.25$; $p = .027$, $g = .82$, and $F(1,47) = 6.89$, $p = .012$, $g = .90$. No significant difference was found between ex-illiterate and literate at any step, including at the smallest: all Fs < 1.

Interestingly, whereas at the 6% size difference, the two groups of readers still had a performance significantly below chance, denoting an Ebbinghaus illusion (ex-illiterate and literate: $t(13) = -2.70$ and $t(14) = -3.06$, both ps $\leq .018$), the illiterate group did not show an illusion, as their performance did not differ from chance, $t(20) < 1$, $p = .86$. In other words, at Step 2, illiterate adults reached the *point of subjective equality, PSE,* also called non-discrimination point or point of non-discrimination (i.e., the point along size difference at which the participants respond at random because they did not significantly detect a difference between the two target circles). In contrast, for readers, regardless of schooling, the illusion was still present, hindering their performance. No group difference was found at larger size differences in the congruent context.

In the incongruent condition, the overall pattern of difference between groups was reversed (Group x Size difference, $F(8, 188) = 2.52$, $p = .017$). To put it differently, illiterate were now less accurate than the two groups of readers, but only robustly at the 2% difference (Step 1), $F(2, 47) = 4.19$, $p = .02$, tended towards significance at Step 2, $F(2, 47) = 2.55$, $p =$

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[7] Effect sizes were calculated using Hedges' g (Hedges, 1981).

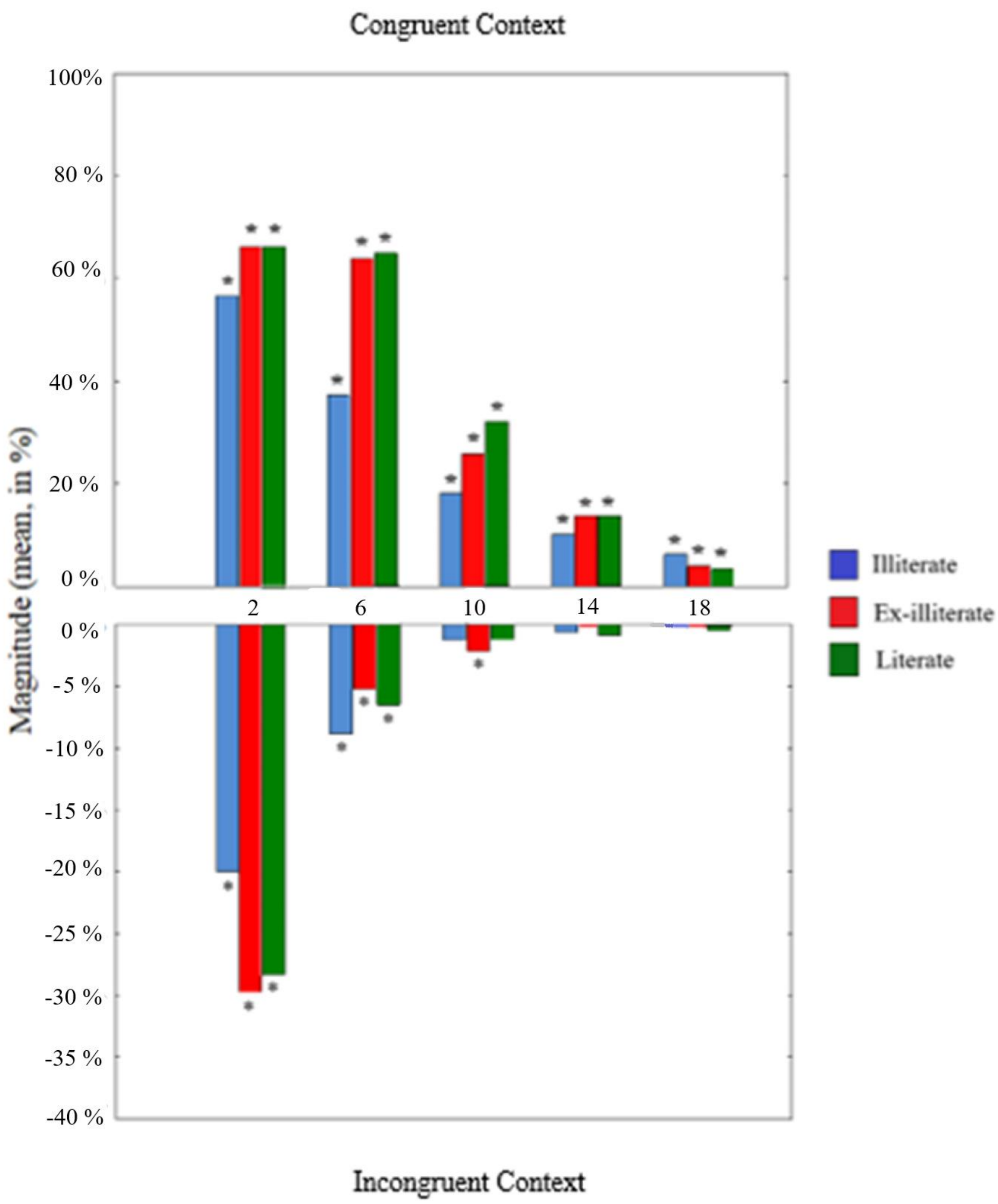
.089, but not at Step 3, $F = 1.73$, $p = .19$, or at any larger size difference. As shown in Figure 6, illiterate were less accurate than ex-illiterate and literate at Step 1, $F(1,47) = 6.35$, $p = .015$, $g = .74$, and $F(1,47) = 5.438$, $p = .024$, $g = .67$, respectively. Again, this is a matter of learning to read regardless of schooling as ex-illiterate and literate did not differ at any step (for Step 1, $F(1, 47) = .05$, $p = .83$). In other words, non-readers were less sensitive to adjacent information either for better or for worse. Illiterate adults showed a disadvantage over the literate groups in incongruent contexts at the smallest size difference, on which the target size would be positively affected by the presence of inducers, but showed an advantage in congruent contexts, on which the size illusion is enhanced, hindering performance.

To better appreciate the modulation by literacy on sensitivity to context in size judgments, we next computed the difference between performance in the context and no context, thus removing from the data the role of veridical size discrimination and visual acuity. Note that positive values indicate that context impairs discrimination (that is, signal an Ebbinghaus illusion), whereas negative values indicate that context enhances size discrimination.

As illustrated in Figure 7, the illusion is indeed stronger in smaller real-size differences in congruent contexts. However, this does not mean that the illusion stops hindering size discrimination at larger real-size differences. In fact, the magnitude of the illusion at each size difference was significant for all groups (compared to a null illusion, all *t*s > 2.00, *p*s < .05). Therefore, even at larger real-size differences between the two circles, the presence of congruent inducers still influenced size discrimination. In the same vein, in the incongruent context, size discrimination was influenced by the presence of inducers, which was stronger at the smaller than larger real-size differences. Yet, this time and in line with prior evidence (e.g., Bremner et al., 2016; Doherty et al., 2008; Doherty et al., 2010; Philips et al., 2004), size discrimination was enhanced by the presence of incongruent inducers.

As shown in Figure 7, incongruent contexts significantly enhanced size discrimination at the smallest size difference of 2 and 6% (compared to a null illusion: all *t*s < -3.00, *p*s < .001, for all groups). However, in step 3, the enhancing context influenced the ex-illiterate, $t(13) = -2.69$, $p = .02$, but not the literate, $t(14) = -1.15$, $p = .27$, or the illiterate, $t(20) = -.55$, $p = .59$.

Figure 7. *Mean illusion magnitude (in percentage) for each size difference in adults*



Note. Top graph represents magnitude in the congruent context, bottom graph represents magnitude in the incongruent context.

* $p < .05$ against a null illusion.

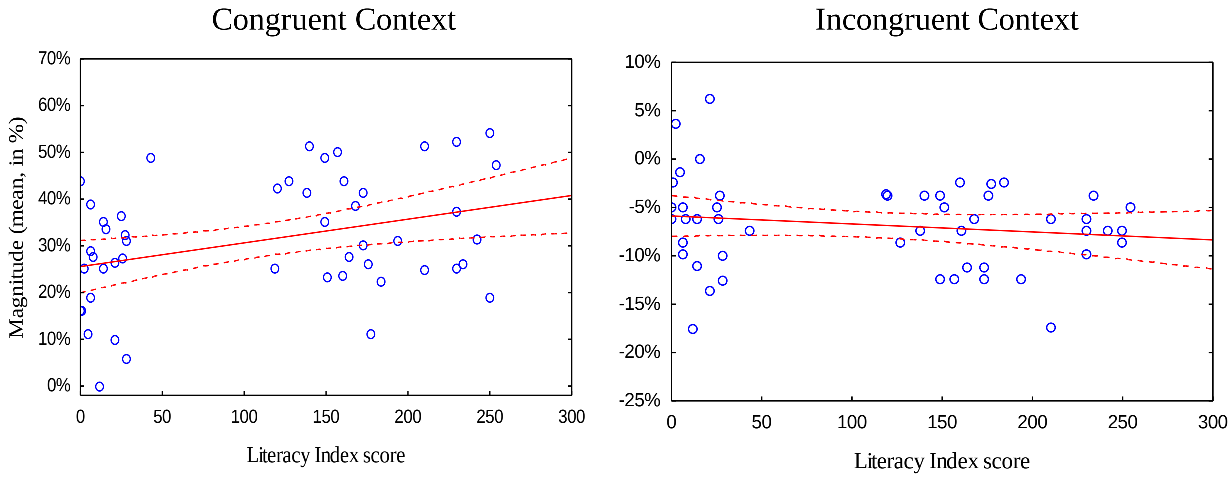
Also, in contrast to what was found in congruent contexts, an incongruent context had no effect at the larger size differences (all $ts < 1.50$, $ps > .1$). This suggests that, at larger real-size differences, participants are not sensitive to the enhancing (incongruent) context. Note that this pattern of results, which differs from the one found in the congruent context, indicates that the two conditions (congruent and incongruent) are not two sides of the same coin, as previously argued by Schwarzkopf and Rees (2013).

The most important contribution of the present experiment is that, regardless of schooling or age at which literacy was acquired, learning to read does seem to play a significant role in the susceptibility to the surrounding information during visual size discrimination. The smaller susceptibility to the surrounding context by non-readers was found both when context enhanced as when it hindered performance. Indeed, illiterate adults had worse size discrimination than the two groups of readers in incongruent contexts, especially when the display potentiated the role of context, that is, when the real-size difference between the two circles was small. In contrast, illiterate adults had better performance in congruent contexts, that is, in the classical Ebbinghaus Illusion, when the illusion is strongest (i.e., at smaller size differences). The latter condition thus revealed a paradoxical result: unschooled illiterate adults were better at size judgments than literate adults in congruent contexts.

The magnitude of the sensitivity to both contexts varied with literacy score in a clear way. As shown in Figure 8, higher literacy was accompanied by more sensitivity to context.

Indeed, whereas veridical size discrimination (without inducers) was neither correlated with literacy or working memory, all $rs(49) < .26$, $ps > .07$, the magnitude of the Ebbinghaus illusion (difference between congruent and no inducers), which is independent from visual acuity and fine spatial discrimination abilities, was significantly correlated with both literacy and working memory: with the literacy index (i.e., summed score across all literacy measures), $r = .37$, $p = .009$, the digit span, $r = .32$, $p = .022$, the corsi block score, $r = .30$, $p = .033$.

Figure 8. *Scatterplots of the relations between magnitude of the sensitivity to both contexts and literacy index score*



Note. Bands represent a 95% confidence interval.

More important, reinforcing the major role of reading in the Ebbinghaus illusion, when we controlled for differences in general cognitive functioning by partialling out the MMSE scores, only the correlation with literacy survived: r = .28, p = .05, but neither the correlation with digit span or corsi block scores (both rs < .24, p > .10). Therefore, these latter correlations were probably due to general cognitive functioning. Furthermore, the impact of literacy is really about the influence of context, regardless of helping or hindering performance, as the same correlation pattern was found, after controlling for general cognitive functioning, between the magnitude of context effects by incongruent inducers and literacy, r = -.28, p = .05 (with digit span: r = .06, p = .68; with corsi block: r = -.13, p = .36).

The present results are consequential in two aspects. First, to the best of our knowledge they are the first to show that such micro cultural object as literacy can influence the Ebbinghaus illusion, in line with previous findings on the impact that learning to read has on visual processing (e.g., Dehaene et al., 2010; Kolinsky et al., 2011; Pegado et al., 2014; Szwed et al., 2012). Second, these results also question the nature of cultural and developmental differences previously reported in the Ebbinghaus illusion.

Regarding cultural effects, previous studies that compared people from western educated industrialized and developed societies, WEIRD (cf. Henrich, Heine & Norenzayan, 2010), with those from rural, unschooled ones, as the Himba (Caparos et al., 2011; Davidoff et al., 2008; de Fockert et al., 2007), on the susceptibility to the Ebbinghaus illusion might have actually been due in part to differences in reading abilities. Of course, these cross-cultural differences are not solely due to literacy acquisition, in fact, the effect size for the differences between our groups of illiterate and ex-illiterate adults (calculated using Cohen's d; d = .58) was smaller than the effect size found for some cross-cultural differences in adults, such as those between Urban Namibians and British (d = 1.77; Bremner et al., 2016). Still, learning to read is a relevant micro-level cultural variable that contributes to differences in the Ebbinghaus illusion.

Our participants shared the same cultural referential, lived in the same environment, and hence, the differences found here between readers and non-readers cannot be attributed to cultural differences at macro level or in exposure to different cluttered environments (e.g. De Fockert et al., 2007; Doherty et al., 2008). Furthermore, differences in exposure to pictures also seem unlikely, given that all three groups were from the same residential backgrounds, and most illiterate were entering the same alphabetization courses as those that ex-illiterate had already finished. Therefore, the present results seem to depend on the acquisition of literacy.

Our results also have implications for previous cultural studies that have shown that cultural differences at macro level (e.g., Himba vs British; Japanese vs Americans) start to emerge exactly at the age where children usually enter school and start learning to read (Bremner et al., 2016; Imada et al., 2013; Köster, Itakura, Yovsi & Kärtner., 2018). Given the strong correlation between reading skills and schooling (i.e. people with more schooling tend to be more fluent readers), literacy, instead of schooling in general, could have been the real factor behind the correlation found between schooling and the Ebbinghaus illusion in Himba participants (Bremner et al., 2016; Experiment 3).

The present pattern of results also questions whether the developmental changes found between preschool and schooled years in the Ebinghaus illusion (e.g., Doherty et al., 2010; Hadad, 2018; Weintraub, 1979; Zannuttini, 1996) are indeed a reflection (or at least mainly) of maturation and cognitive development. To examine whether learning to read is indeed critical for the changes found in the Ebbinghaus illusion between preschool and school years, in Experiment 2, we examined pre-literate and first-grade children that were matched in age, sex, sociocultural and economic environment, and cognitive development, but who differed only in schooling and literacy.

Experiment 2

Method

Participants

Thirty-nine Portuguese six-year-old children, without known history of developmental and/or neurological disorders, participated voluntarily after parents gave written informed consent. Given that, in Portugal, children enter primary school (when literacy instruction starts) between five and seven years old, we selected two groups matched in sex, $X^2(1) < 1$, $p = .42$, age, $t(37) < 1$, $p = .98$, and in several cognitive abilities (see below and Table 4). They only differed in literacy/schooling: 19 pre-literate preschoolers (7 boys; *M*age = 76.10 months, *SD* = 0.86) and 20 first graders (5 boys; *M*age = 76.10 months, *SD* = 0.85).

Materials and Procedure

Ancillary tests.

Before the experimental task, children were assessed in five domains, using a similar rational as in Experiment 1: (i) *nonverbal intelligence* (Colored Progressive Matrices of Raven, *CPM*, Portuguese Version; Simões, 2000); (ii) *verbal intelligence* indexed by the vocabulary subtest of the *Wechsler scales for children* (i.e., Wechsler Preschool and Primary Scale of Intelligence, 3rd ed.; Wechsler, 2002, Portuguese version: Simões et al., 2003); (iii) *verbal working memory* (digit span subtest of WAIS-III, Portuguese version: Wechsler, 2008); (iv) *visuospatial working memory* (Corsi blocks test from the Wechsler Memory Scale, 3rd ed.; Wechsler, 1997); (v) *letter knowledge* (letter naming). These latter three tests were the same as those used in Experiment 1.

We ensured that none of the preschoolers was able to decode any word or pseudoword, but varied on letter knowledge (from 2 to 43 letters correctly named). Therefore, we also computed the *literacy index* presented in Experiment 1, but here for preschoolers and for first graders (i.e., the summed score for letter knowledge and the reading tasks described below).

Reading skills were fully assessed in first graders. They performed an offline reading aloud task of six words (i.e., vaca, cola, nariz, mesa, amiga, anexo) and six pseudowords (i.e., cau, vapa, pesta, benino, tavalo, jalada) without time limit. We also examined whether they already showed automatic reading skills with the reading fluency subtest of 3DM (Reis et al., in preparation). As shown in Table 3, first graders had already some ability to decode but very insipient reading fluency. Reading comprehension was assessed with *TIL* (Sucena & Castro, 2008), but given that only one first grader had a score above zero (able to correctly perform seven items in the allotted time of 5 min), this test was not considered. Therefore, these first graders were at the very beginning of literacy acquisition. This allowed us to examine whether size discrimination and specifically the Ebbinghaus illusion was influenced by reading skills, even if insipient, under a schooling context (first graders were already able to read aloud some items of the offline reading task). As shown in Table 3, the two groups differed in letter knowledge: first graders correctly named more letters than preschoolers (besides having reading skills); consequently, the groups also differed in the literacy index.

More important, the two groups were well matched in cognitive development (besides age and sex). As shown in Table 3, they did not differ in nonverbal or verbal intelligence nor in working memory, either visuospatial or phonological.

Experimental material and procedure.

The same as in Experiment 1, except that here it was the experimenter (and not the participant) that pressed the response keys which corresponded to the circle chosen by the child by pointing to ensure that children were focused on the experiment throughout the session.

Table 3

Average Performance in the Ancillary Tests for preschoolers and first graders

	Preschoolers (n = 19)	First graders (n = 20)	Group comparison, *t*(37)
Nonverbal IQ: CPM (out of 36)	20.95 (4.73)	18.70 (4.91)	$t(37) = -1.45$, $p = .15$
Verbal IQ: Vocabulary	25.11 (4.18)	25.00 (5.40)	$t < 1$
Visuospatial working memory: Corsi blocks	9.32 (2.45)	9.95 (2.39)	$t < 1$
Phonological working memory: Digit span	8.42 (1.61)	8.50 (1.64)	$t < 1$
Letter naming (out of 46)	19.79 (13.11)	33.45 (11.20)	$t(37) = 3.50$, $p = .001$
Reading			
Offline task (12 items)	0	4.60 (3.57)	
3DM, high-frequency words	0	2.10 (3.02)	
3DM, low-frequency words	0	1.70 (2.47)	
3DM, pseudowords	0	1.65 (2.60)	
Literacy index	19.79 (13.11)	43.50 (20.42)	$t(37) = 4.29$, $p < .001$

Note. SD in parentheses; performance in all tests was computed as total of correct responses.

Results and Discussion

Like in Experiment 1 with adults, the results of children revealed the influence of literacy in sensitivity to the surrounding context during visual size discrimination. In the mixed ANOVA run on raw scores (total correct responses) with group (preschoolers; first graders: between-participants), context (no context; congruent; incongruent) and size difference (2; 6; 10; 14, 18) as within-participants variables, as hypothesized, the interaction between group and context was significant, $F(2, 74) = 3.31$, $p = .042$, $\eta p^2 = .082$, $MSE = 28.03$ (main effect of group, $F(1, 37) = 3.41$, $p = .09$, $MSE = 22.34$).

Table 4
Mean accuracy (in %) *of the two groups in each context*

	First graders	Pre schoolers	Across-groups
No Context	84.48 (7.35)	84.89 (6.81)	52.08 (22.13)
Congruent	45.01 (19.12)	59.52 (23.10)	90.92 (10.59)
Incongruent	91.49 (11.92)	90.32 (9.28)	84.68 (7.00)

Note. SD in parenthesis.

As shown in Table 4, when the circles had no surroundings (i.e., no context), preschoolers were as able as first graders to perform veridical size judgments, $F < 1$. In contrast, pre-literate preschoolers were significantly better than first graders in size discrimination when the circles were surrounded by congruent inducers, $F(1, 37) = 4.58$, $p = .039$, $MSE = 57.21$. In other words, the two groups significantly differed in the susceptibility to the Ebbinghaus illusion, which was larger for readers than non-readers, $F(1, 37) = 4.21$, $p = .047$, $MSE = 29.44$. Yet, both showed an illusion: lower accuracy (across size difference) in congruent than in no context, for preschoolers, $F(1, 37) = 26.63$, and first graders, $F(1, 37) = 67.81$, both *p*s < .001.

Note that preschoolers and first graders did not differ on performance in the no context condition and neither in sex, chronological age, or cognitive development (i.e. they did not differ in nonverbal or verbal intelligence, or in phonological or visuospatial working memory measure, see Table 3). Therefore, the difference on susceptibility to the Ebbinghaus illusion reported here is most likely due to learning to read. The role of schooling in general cannot, of course, be discarded. However, based on our results in Experiment 1, it is clear that literacy plays a bigger role than schooling in the influence of context in visual size judgments and specifically in the susceptibility to the Ebbinghaus illusion. Unschooled ex-illiterate and schooled literate adults showed virtually the same pattern of results in Experiment 1, both differing from unschooled illiterate.

The Ebbinghaus illusion is revealed by a performance significantly below chance (50%, that is of 8 out of 16 correct responses), which would depend not only on the presence of inducers but also on the size difference between the two target circles. Indeed, as in Experiment 1, the main effects of context and size difference were significant, $F(2, 74) = 76.67$, and = 162.69, ηp2 = .674 and = .815, *MSE* = 0.109 and = 0.012, both *p*s < .001, as well as their interaction, $F(8, 296) = 32.91$, $p < .001$, $\eta p^2 = .471$, *MSE* = 0.011.

Note that preschoolers and first graders did not differ in the incongruent context, $F < 1$, and both showed an advantage on size judgments in the incongruent than in no context: preschoolers, $F(1, 37) = 4.82$, $p = .034$; first graders, $F(1, 37) = 8.34$, $p = .006$. In line with previous evidence (e.g., Bremner et al., 2016; Doherty et al., 2008, 2010) and the results of Experiment 1, observers seem to be more sensitive to an impairing (congruent) context than to an enhancing (incongruent) one in size discrimination (Doherty et al., 2010).

Note that, in Experiment 1, the influence of a misleading (congruent) context was found across all steps, even at the larger ones, whereas the influence of an helpful (incongruent) context was limited to a 2 and 6% size difference. However, this difference could be attributed to ceiling effects at the larger size difference in the former context, which would have left less room for a visible impact of both the surrounding information and of literacy in size discrimination. Noteworthy, in contrast to adults (Experiment 1), where ceiling was reached, that is, accuracy did not differ from 100%, at 10% size difference for the incongruent context and at 18% size difference for the no context (see Figure 7), in children, accuracy was significantly below ceiling, that is, of 100% (score of 16), at any size difference, including the larger ones, in both incongruent and no context (across size difference, for preschoolers and first graders, in incongruent context: 90.32 and 91.49%, SD = 9.28 and 11.92, respectively; in no context: 84.89 and 84.48%, SD = 6.81 and 7.35, respectively, all *t*s < -2.66, $p \leq .015$) and still, for children, the impact of an enhancing (incongruent) context relative to no context was found only at the 2 and 6% size difference, $F(1, 37) = 62.26$ and $= 11.90$, both $ps < .0001$, not at larger size differences (from 10 to 18%, $F\text{s} \leq 2.68$, $p \geq .11$). In contrast, the presence of congruent (impairing) inducers led to worse performance than no inducers in size discrimination by children at every size difference, including the larger ones, all $F(1, 37) \geq 25.70$, $p\text{s} < .0001$. This pattern of results clearly shows that the asymmetric impact of congruent vs. incongruent context in size discrimination is not a mere consequence of ceiling effects in the latter context but rather because these contexts are not two sides of the same coin. This result also reflects the idea that contextual effects depend on the interaction between size of inducers and the target, probably due to the complex pattern generated by contour interaction when size is congruent or incongruent (e.g., Jaeger, 1978; 2015). Furthermore, the fact that children did not reach a ceiling performance in no context even at the larger size difference (as aforementioned), in contrast to adults, also suggests that veridical size discrimination might not have completely matured until the age of six.

In contrast to Experiment 1, the three-way interaction was not reliable (Group x Size difference, $F < 1$). We nonetheless decomposed it for five reasons. First, based on prior evidence (e.g., Bremmer et al., 2016; Doherty et al., 2008, 2010) and on the results of Experiment 1, the Ebbinghaus illusion is usually stronger at smaller than larger size differences. Second, we had an a priori hypothesis that larger differences would be found between groups at the smallest size differences, where the influence of literacy in the Ebbinghaus illusion would have enough space to be robust. Third, in the present experiment we did find an overall impact of learning to read in the Ebbinghaus illusion, as denoted by the robust interaction between group and context. Fourth, another way of checking the impact of learning to read in the Ebbinghaus illusion is to examine the location of the PSE in each group, that is, the point at which readers and non-readers are no longer tricked by the presence of inducers (that is, the point at they no longer have a performance significantly below chance). Finally, the results of

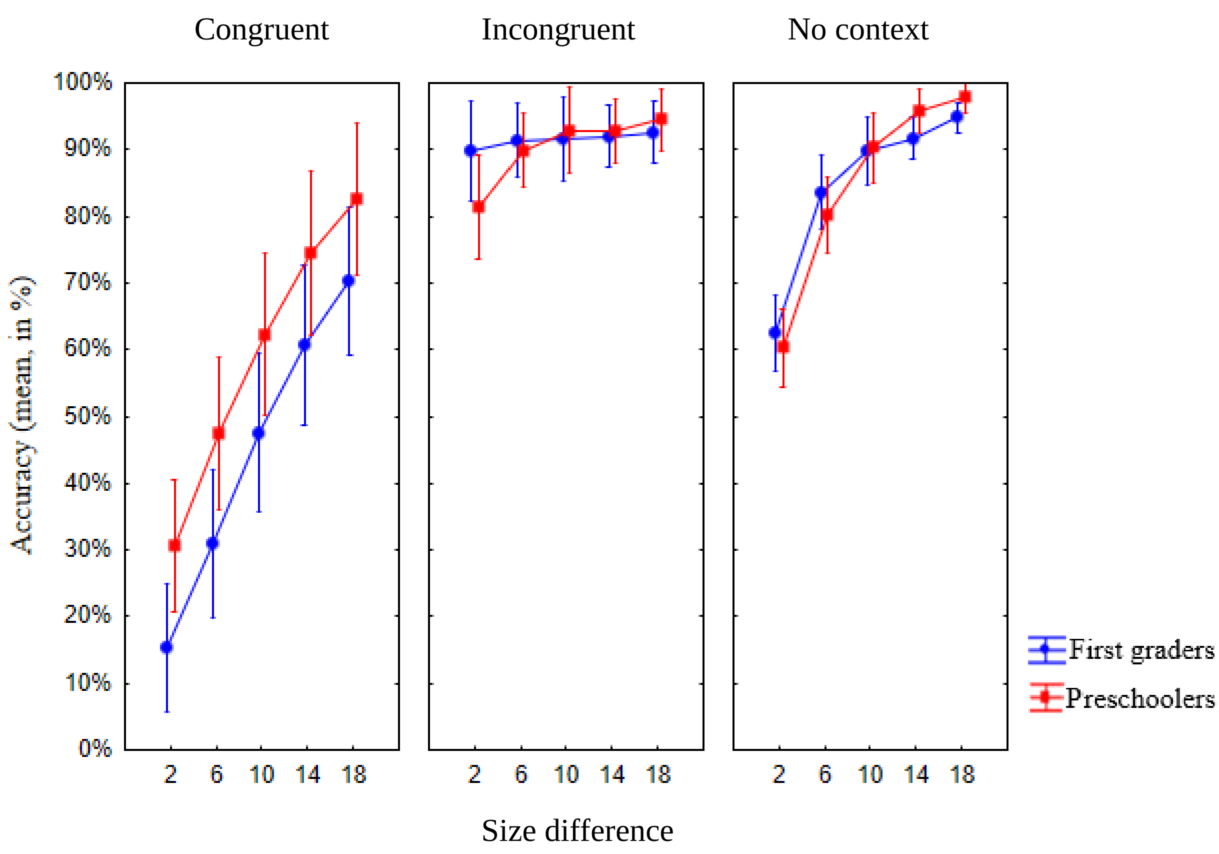
Experiment 1 with illiterate, ex-illiterate and literate adults were clear cut on this evidence: the impact of learning to read was mainly found at the smaller size differences.

As expected (see Figure 9), the main effect of size difference was significant in all contexts: size discrimination was harder the smaller the size difference between the target circles in any context: none, $F(4, 148) = 115.27$, $MSE = 1.72$; congruent, $F(4, 148) = 86.81$, $MSE = 5.32$; and incongruent, $F(4, 148) = 6.24$, $MSE = 1.59$, all $ps \leq .0001$. In no context, the interaction between group and size difference was not significant, $F < 1$, because literacy did not impact veridical size judgments (when no surrounding information was available). We next checked whether, just like we found in Experiment 1, literacy influenced the Ebbinghaus illusion mainly at the small size differences in the congruent and incongruent contexts.

In the congruent context, similarly to the results of Experiment 1, preschoolers were more accurate than first graders at 2 and 6% size difference, $F(1, 37) = 5.05$, $p = .030$, $MSE = 11.53$ and $F(1, 37) = 4.36$, $p = .044$, $MSE = 15.45$, but this difference only tended towards significance at 10% difference, $F(1, 37) = 3.02$, $p = .090$, $MSE = 17.78$, and the groups no longer significantly differed at 14 and 18% size difference, $F(1, 37) < 2.60$, $p > .11$. This clearly shows the larger impact of learning to read in the Ebbinghaus illusion at smaller size differences. Furthermore, whereas at the 6% size difference first graders had a performance significantly below chance, denoting an Ebbinghaus illusion, $t(19) = -3.72$, $p = .001$, pre-literate preschoolers did not show an illusion, as their performance did not differ from chance, $t(18) < 1$, $p = .67$. In other words, at Step 2, that is, 6% size difference, the pre-literate children reached the PSE, whereas for first graders the illusion was still present, hindering their performance. It thus took less for non-readers to break from the illusion than readers.

In contrast to what was found in the congruent context, in the incongruent (helpful) context there was no difference between groups even at the smallest, 2%, size difference, $F(1, 37) = 2.48$, $p = .12$, $MSE = 1.40$ (at other size differences, Fs < 1).

Figure 9. *Accuracy in each size difference for first graders and preschoolers*

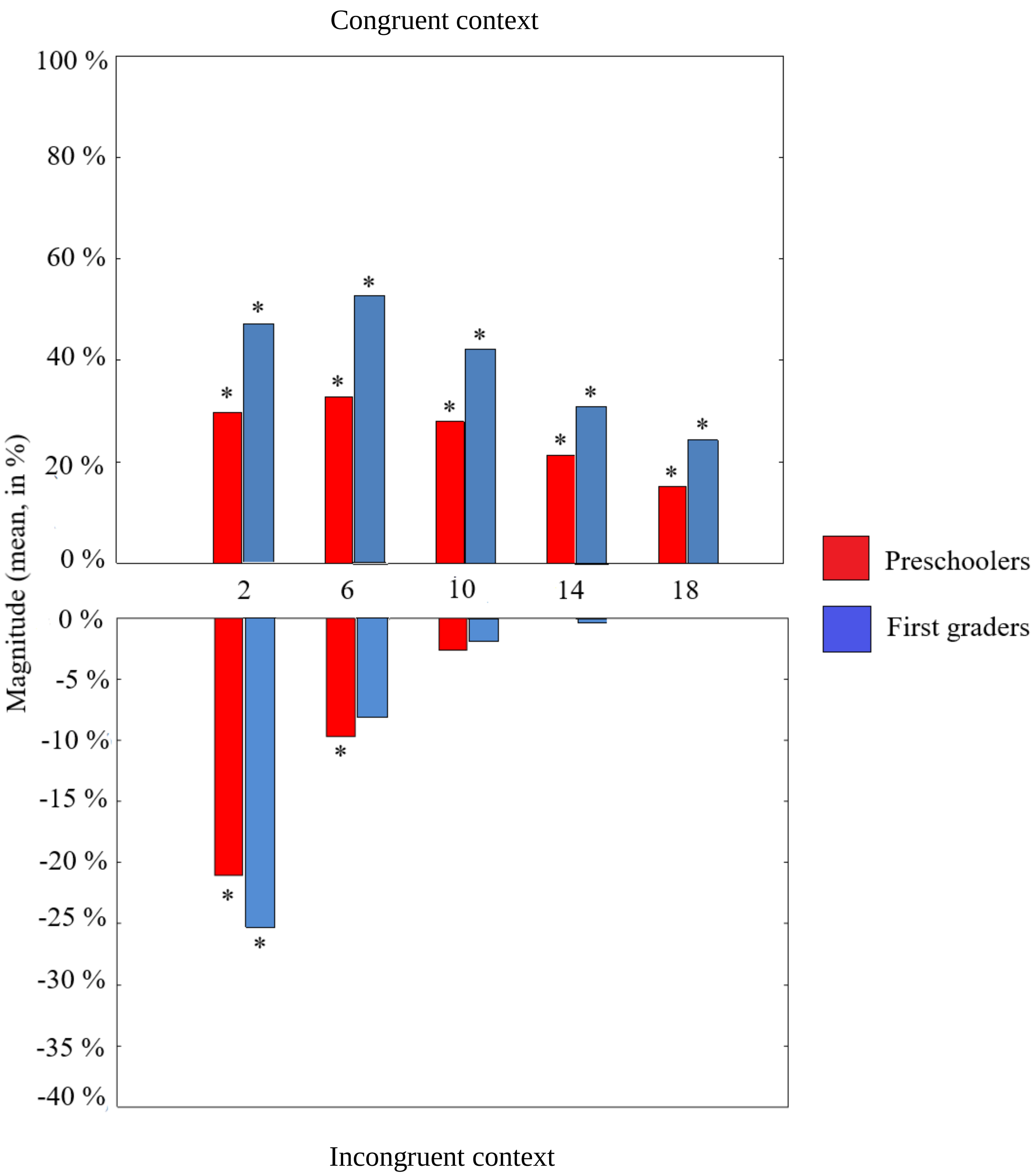


Note. Error bars represent the SEM - standard error of the mean.

To further investigate the effects of literacy on context sensitivity, as well as the asymmetry between congruent and incongruent contexts, we computed the magnitude of contextual effects in the congruent and incongruent contexts relative to no context for first graders and preschoolers, as we did in Experiment 1. As illustrated in Figure 10, the illusion was once again stronger in smaller size differences in congruent contexts. Even so, a misleading context influenced size discrimination at all size differences (when compared against a null illusion: all *t*s > 2.90, *p*s < .01).

As shown in Figure 10, like in Experiment 1, there was an asymmetry in the influence of context between congruent and incongruent surroundings. In incongruent contexts there was consistently smaller (helpful) impact of surrounding than in congruent (misleading) contexts, where an Ebbinghaus illusion occurred. In the incongruent context, sensitivity was stronger at smaller size differences.

Figure 10. *Mean illusion magnitude (in percentage) for each size difference in children*



Note. Top graph represents magnitude in the congruent context (magnitude of the Ebbinghaus illusion), bottom graph represents magnitude in the incongruent context.

* $p < .01$ against a null illusion.

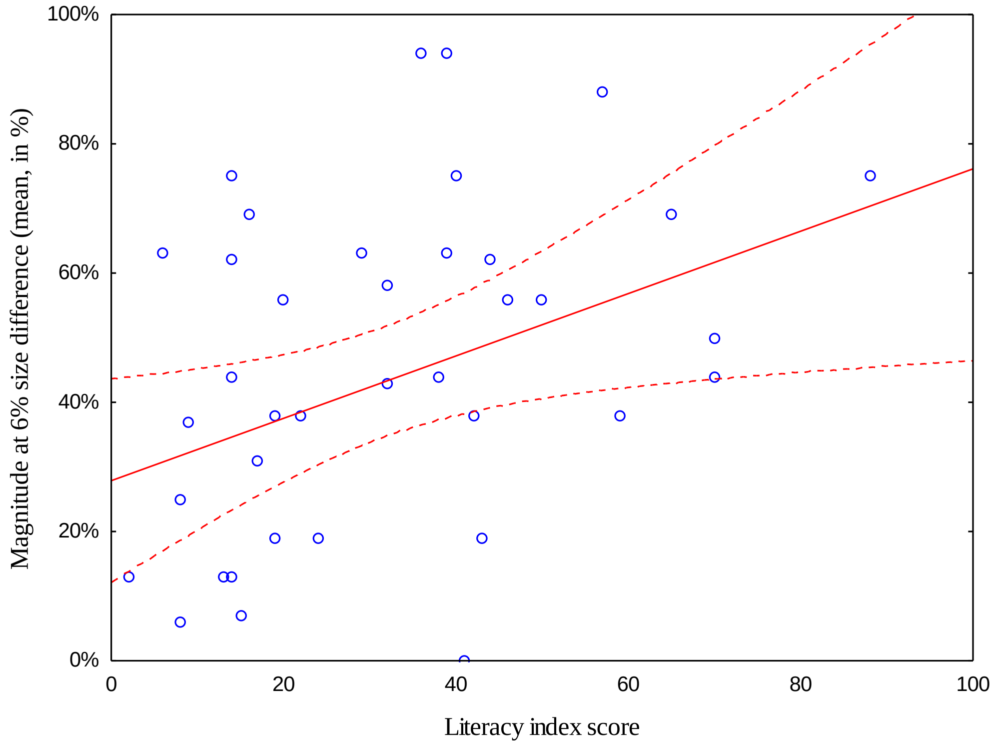
For preschoolers, size discrimination was affected by the helpful context at 2 and 6% size differences, $t(18) = -4.42$, $p < .001$, and $t(18) = -2.90$, $p < .01$, respectively. First graders were influenced by the helpful context at 2% size difference, $t(19) = -5.90$, $p < .001$, but only marginally at 6% size difference, $t(19) = -2.04$, $p = .06$. Neither group was influenced by context at the 10 and 14% size differences (all *t*s > -1.1, *p*s < .3). At the 18% size difference, the incongruent context significantly impaired size discrimination by preschoolers, $t(19) = 2.14$, $p = .05$ and had no effect for first graders, $t(18) = .75$, $p = .46$. This shows once again that the incongruent context has no effect at larger size differences.

Finally, we examined whether reading and other cognitive abilities were correlated with the Ebbinghaus illusion and sensitivity to the context, considering the literacy index, phonological and visuospatial working memory (digit span and corsi blocks test, respectively), and nonverbal and verbal intelligence (CMP and vocabulary scores). In contrast to what was found in Experiment 1, veridical size judgments (no context) were significantly correlated with visuospatial abilities, that is, with visuospatial working memory (corsi blocks score) and nonverbal intelligence (CPM), $r(37) = .49$ and $r(37) = .52$, respectively, *p*s < .005. In what regards the literacy index and the vocabulary score, no significant correlation with veridical size judgment was found, $r(37) = -.04$, and $r(37) = -24$, respectively, both *p*s > .15.

In what regards the magnitude of contextual effects in congruent (misleading) and incongruent (helpful) contexts, no significant correlation was found for neither congruent (all *r*s < .23, *p*s > .15) nor incongruent contexts (all *r*s > -.15, *p*s > .35). Partial correlations were also unreliable, all *p*s > .13.

It might, however, be the case that the correlation between literacy/schooling and the Ebbinghaus illusion was reliable at the smaller size differences, where there was enough room to find a moderator role of literacy in sensitivity to context, that is, at the 6% size difference. Note that, as aforementioned, it was at this size difference that the differences between groups were the largest (see Figure 10). Indeed, at 6% size difference, the better the children's literacy skills the larger the Ebbinghaus illusion, $r = .33$, $p < .05$ (see Figure 11), which, in turn, was not significantly correlated with any other cognitive ability, all *r*s < .27, *p*s > .09.

Figure 11. *Scatterplot of the relation between magnitude of the sensitivity to the congruent context at 6% size difference and literacy index score*



Note. Bands represent 95% confidence intervals.

The present experiment provided further evidence for the role of literacy in the susceptibility to the Ebbinghaus illusion: pre-literate preschoolers were less susceptible to a misleading impairing (congruent) context than first graders who were just beginning readers. Given our strict control in cognitive abilities and age, neural maturation cannot be responsible for the difference found between the two child groups examined here, who were from close neighborhoods, from the same city and from the same socioeconomic and cultural background. The similarities between the results of Experiments 1 and 2 suggest that it is not exposure to pictorial information but rather learning to read (and not just only exposure to print) that influences sensitivity to contextual information. The present results raise the question of whether previous developmental studies on the Ebbinghaus illusion that showed the largest difference between preschool and school years (e.g., Doherty et al., 2010; Hadad, 2018) were indeed tapping into a developmental change instead of a byproduct of an experience-based (reading) modulation.

General Discussion

In the present thesis we explored the potential role of learning to read on visual context integration and specifically on the Ebbinghaus illusion. To this aim, in two experiments, we compared readers and nonreaders (in Experiment 1, uschooled ex-illiterate and schooled literate vs. illiterate adults; in Experiment 2, first graders vs. pre-literate preschoolers), in order to provide convergent evidence and also to determine if development plays a significant role in sensitivity to context independently of literacy acquisition.

The most important contribution of the present work is that learning to read has a significant impact in the influence of visual context in size discrimination. As expected, non-readers were less sensitive to a misleading (congruent) context than readers, which meant that illiterate adults and pre-literate children were less susceptible to the Ebbinghaus illusion than observers with reading skills. In Experiment 1, similarly to previous studies with adult groups (e.g., Doherty et al., 2008; Phillips et al., 2004), the difference between groups was larger at the small size differences. Therefore, illiterate adults were more accurate in size discrimination of an inner target surrounded by congruent size inducers (the classic Ebbinghaus illusion) than ex-illiterate and literate adults. In Experiment 2, pre-literate preschoolers were more accurate in size discrimination for the congruent context compared to first graders learning to read, and, once again, this was especially evident at smaller real-size differences.

In both experiments, the influence of context was not symmetrical in the congruent and incongruent surroundings. Accordingly with our hypothesis, in Experiment 1, illiterate were less accurate in the incongruent context compared to both ex-illiterate and literate adults. This was especially evident when the display potentiated the role of context, that is, at smaller real-size differences between the target and the comparison circle. In Experiment 2, however, literacy did not modulate sensitivity to this context: pre-literate preschoolers did not differ from first graders overall, nor in any size difference.

In a way, this was not surprising, the incongruent context had never been used in another experiment at more than 2% size difference, so the incongruent and congruent contexts have never been shown to be equivalent counterparts. In fact, both our experiments clearly indicated that the congruent and incongruent context are not two sides of the same coin. Sensitivity was overall larger to the congruent context: while there was a clear illusion effect for every size difference, the effect of the incongruent context was limited to the 2 and 6% size differences. This was not due to ceiling effects, given that, while adults did reach a ceiling effect at 10% size difference, children did not, yet we found that the incongruent context only had an effect at the smaller size-differences in both experiments. Noteworthy, even at these size differences, the magnitude of the sensitivity to the incongruent context was reduced considerably compared to the magnitude of the sensitivity to the congruent context (see figures 7 and 10). This clearly demonstrates that the incongruent context is not an equivalent counterpart of the congruent context, which would be the case if size contrast mechanisms were the only ones involved (Doherty et al., 2010; Weintraub, 1979). Yet, these contexts did differ, regarding the nature of contour interactions taking place. The distance between the inner circle and the outer contours of large inducers is always larger in incongruent compared to congruent contexts. Therefore, the outer contours of large inducers will have larger expression in the repulsion zone (see Figure 2A) in incongruent than congruent contexts, and hence, their impact on size estimation of the inner circle will be stronger when the inner circle is smaller (incongruent condition) than larger (congruent condition). In the same vein, small inducers will be closer to the inner circle when this inner circle is larger (incongruent context) than when it is smaller (congruent contexts), so the outer contours of small inducers will have larger expression in the attraction zone (Figure 2A) in the former context, and, hence, their impact on size estimation of the inner circle will be stronger in the incongruent compared to the congruent context. Therefore, regardless of the size of inducers, the distance between the inner circle and the outer contours depends on congruency of size between inducers and target, which would not be symmetrical in terms of the interaction between attraction and repulsion effects. This reveals the challenge of controlling for contour interactions when studying the Ebbinghaus illusion, because even when the distance between inner contours of inducers and target is controlled, the distance to the outer contours will vary depending on the size of target and inducers. It is thus difficult to understand the observation of Doherty et al. (2010), who claimed that contour interactions play no part in their results, due to their control of the distance between the inner circle and the inner contours of inducers, given that outer contours still affected performance.

In order to examine if factors other than literacy played a role in the susceptibility to the Ebbinghaus illusion, we compared the difference in illusion magnitude between readers and non-readers in children and adults. However, there are two issues that must be taken into account when doing this comparison. Firstly, there might still be influences of cognitive development interacting with veridical size perception for children. In fact, our Experiment 2 suggested this, namely we found a relation between both CPM and Corsi block scores and performance on the condition without inducers, which we have interpreted as reflecting the immaturity of visuospatial abilities in six-year-old children, so it is not surprising that first graders differed from ex-illiterate and literate adults on visual acuity (both $ts < -3.7$, $ps < .001$). Magnitude measures must be used to control for this. Second, it is not clear if maturation influences the susceptibility to the Ebbinghaus illusion in a purely quantitative way, it might influence the way in which the illusion affects size discrimination, and not only how much it affects size discrimination. Studying these qualitative differences would require the analysis of the slope of psychometric functions, which, while out of the scope for the present study, should be something to consider in future studies that compare children and adults in the susceptibility to the Ebbinghaus illusion.

Given that literacy effects were strongest at 6% size difference in the congruent context (see figures 7 and 10), we measured the magnitude of sensitivity to the congruent context at 6% size difference for the readers in both experiments relative to the non-readers. In Experiment 1, relative to illiterate adults, ex-illiterate and literate adults were 27% (SD = .36) and 28% (SD = .40) more influenced by the congruent context at this size difference. In Experiment 2, first graders were 19% (SD = .38) more influenced by the congruent context at this size difference than pre-literate preschoolers. At least numerically, the magnitude of the illusion by child readers relative to non-readers is smaller than the one of adult readers relative to illiterate adults. This might suggest that, besides literacy acquisition, other factors are also involved in the Ebbinghaus illusion, including development. However, given that we did not examine children at other ages, we can only speculate whether development, schooling, or other factors could be involved. Future studies could consider this possibility .

The present results agree with previous findings on the impact of literacy in visual integration abilities (Szwed et al., 2012). At a neural level, both the Ebbinghaus illusion paradigm employed here and the contour integration task employed in Szwed et al. (2012) are suggested to depend on long-range connections within V1 that link cells with similar tunning preferences (Hadad et al., 2010; Gervan & Kovács, 2010; Kovács, 2000; Kaldy & Kovács, 2003; Li & Gilbert, 2002; Schwarzkopf et al., 2011; Schwarzkopf & Rees, 2013). Therefore, our results, along with the results of Szwed et al. (2012), suggest that literacy can impact early visual areas, specifically V1, with changing these long-range connections within V1 through a perceptual learning process. It should be noted, however, that there is not direct evidence to support that the Ebbinghaus illusion is related with both contour integration and axonal plasticity in V1, given that only invasive techniques (i.e. techniques that require surgery) can provide a direct look into synaptic connections within V1, but such techniques are not used with humans due to ethical considerations. However, a recent study by van Kerkoerle et al. (2018) has demonstrated axonal plasticity in V1 following contour integration training in adult macaques using such invasive techniques. One way to provide direct evidence for the links between the Ebbinghaus illusion and both contour integration and axonal plasticity in V1 would be to test these macaques in the Ebbinghaus illusion during two phases: pre-training and post-training in the contour integration task. Finding that the Ebbinghaus illusion does increase in magnitude after training would provide evidence for a direct association between the Ebbinghaus illusion and both contour integration and axonal plasticity in V1.

The impact of literacy acquisition on early visual processing had already been implicated in studies demonstrating that extensive experience with written print iniciates a process of perceptual learning that adapts early visual areas to the shapes that compose letters. For example, literate adults show increased fMRI activation in V1/V2 for scrambled word stimuli in comparison to well-matched scrambled controls on a task that was designed to minimize top-down influences (Szwed et al., 2011; 2014). They also show increased fMRI activation in the same areas for letters and mached symbols compared to rotated versions of the same shapes (Chang et al., 2015). Furthermore, these benefits from perceptual learning are not limited to letters, Dehaene et al. (2010) found that literacy enhanced responses in V1 not only to written words, but also to horizontal checkerboards presented at the foveal and horizontal location in which words are commonly perceived (Rayner, 1998), but not for vertical checkerboards. Our study goes beyond this, however, by specifically suggesting that perceptual learning, driven by literacy acquisition, impacts the highly plastic horizontal long-range circuits of cells within V1 (Gilbert et al., 1996; Kovács et al., 1999; Li & Gilbert, 2002; Li et al., 2004; 2008; McManus et al., 2011; Schwarzkopf & Kourtzi, 2006). Notably, this impact might occur very early during reading acquisition, given that our results demonstrated that literacy effects were already very evident in children who still lacked in reading fluency skills. It has been shown that literacy impacts late visual areas (e.g. the ventral occipitotemporal cortex) as early as two months after reading training (Dehaene-Lambertz et al., 2018), however, the impact on early visual processing has never been tracked across reading acquisition before, our study suggests that it also occurs rapidly.

It should also be further studied if the impact of literacy in early visual processing is widespread over the central visual field[8], or if, as suggested by Dehaene et al. (2010), it is limited to the portions where words are usually read. The reason for this is that our study employed stimuli that is perceived differently from the way in which words are perceived. For example, while letters are preferentially linked horizontally in order to form words, our central circles were always flanked by horizontal, vertical and diagonal contours. Besides, the benefits of perceptual learning in one trained portion of the central visual field can transfer to a larger untrained portion (Crist et al., 1997; Song et al., 2017), depending on the stimuli and training task. One way to study this would be to compare readers and non-readers in different Ebbinghaus stimuli where the inducers are presented only horizontally or only vertically. If perceptual learning following literacy is restricted to certain portions of the retinotopic cortex where words are usually perceived, then, similarly to what Dehaene et al. (2010) found for checkerboards, literacy effects should occur only for the Ebbinghaus stimuli in which inducers are presented horizontally.

Our findings also shine some light on the nature of cultural and developmental differences found in the susceptibility to the Ebbinghaus illusion. The present results argue against an all-encompassing notion of culture, that can, by itself, explain cross-cultural differences in perception. Instead, they suggest that the mechanism responsible for these cultural changes is not necessarily about culture but about experience-dependent perceptual learning, as others have suggested (e.g., Dehaene et al., 2015; Gilbert & Li, 2012; van Kerkoerle et al., 2018). Therefore, we argue that literacy acquisition is a relevant micro level cultural

[8] It has been shown that the Ebbinghaus illusion is more dependent on cortical magnification in V1 rather than absolute anatomical area of V1, which suggest that this illusion is more dependent on central vision rather than also depending on foveal vision (Schwarzkopf & Rees, 2013).

variable that influences sensitivity to context through perceptual learning.

Considering the suggestion that this illusion depends on horizontal connections within V1 (Kaldy & Kovács, 2003), we suggest that cross-cultural differences in perception occur through cultural practices that affect early levels of visual processing. In line with this, Sigman et al. (2005) have noted that extensive training on a specific shape (e.g., an inverted T) shifts the cortical representation of this learned shape from higher to lower visual areas so that more efficient and less effortful processing is achieved. As a consequence, activity also becomes progressively reduced in the frontoparietal attentional network (Sigman et al., 2005), denoting that processing does become less effortful with perceptual training. Indeed, at least in what regards contour integration and V1 functioning, a consistent and extensive literature has shown their dependence on perceptual learning and experience-based modulations, both at the lab (Kovács et al., 1999; Experiment 2; van Kerkoerle et al., 2018) and in real life (e.g., Szwed et al., 2012). Therefore, the coincidence in time between the developmental change found in contour integration (Kovács et al., 1999) and an experience-based change, dependent on learning to read (Szwed et al., 2012), which, in turn, is known to affect V1 responsiveness to visual nonlinguistic categories (Dehaene et al., 2010; Dehaene-Lambertz et al., 2018) is unlikely to be by chance.

Therefore, as we have suggested, the same impact of learning to read is at least one of the causes for the developmental turn-point systematically found in the Ebbinghaus illusion between 5- and 7-year-old children (e.g., Bremner et al., 2016; Doherty et al., 2010; Hadad et al., 2018, Kovács et al., 1999; Weintraub, 1979). Note that this illusion depends on contour interactions (e.g., Jaeger, 2015, 1978; Jaeger et al., 2014; Rose & Bressan, 2002; Schwarzkopf & Rees, 2013; Todorovic & Jovanovic, 2018) and is underpinned by V1 functioning (e.g., Chen et al., 2018; Schwarzkopf & Rees, 2013; Song et al, 2011) and the plexus of horizontal long-range connections at V1 (Kovács et al., 1999; Li & Gilbert, 2006). Therefore, the present findings that, at the age of six, the magnitude of the Ebbinghaus illusion depends on learning to read suggest that what seems to be a developmental change is instead a modulation by perceptual learning resulting from the intensive visual activity that is reading (McCandliss, Cohen, & Dehaene, 2003). Note that we are not the first to propose that exposure to print is relevant for modulations of the Ebbinghaus illusion (Bremner et al., 2016; Doherty et al., 2010). Nonetheless, we are the first to show objectively that, from a very early phase of reading development (in beginning readers from the 1st-grade), changes induced by learning to read in neural underpinnings which also serve visual processing of pattern configurations and which are not (at least apparently) related to print can already be visible. We are not arguing that these changes can only happen with learning to read, although when not properly controlled (e.g., Himba unschooled adults compared with Britsh college students; preschoolers compared to first graders), what seems to be due to culture at macro-level or development might rather be explained by a micro cultural object as literacy. Instead, what we propose is that the mechanism responsible is experience-dependent perceptual learning that taps into the processes involved in contour interaction.

Furthermore, given the large differences between written scrips in Western and some East Asian cultures (such as Japanese and Chinese), learning to read in different scripts might influence differently the susceptibility to the Ebbinghaus illusion, even if both groups are literate. In fact, while the structural characteristics of alphabetic scripts are simple left-right linear layouts of letters, the structural characteristics of non-alphabetic scripts, like the Japanese (kanji and kana) and Chinese scripts, are complex visual-spatial configurations in a two-dimensional square. Therefore, learning to read in these latter scripts might place greater demands on holistic visuo-spatial processing compared to alphabetic scripts (e.g. Cao, Brennan & Booth, 2015), which could, in turn, influence the susceptibility to the Ebbinghaus illusion to a greater degree.

We hope that, following our study, the role of literacy will be placed in higher consideration when contrasting schooled and unschooled groups. Considering our results, this is, of course, particularly relevant when considering the Ebbinghaus illusion, but the impact of literacy should not be limited to Ebbinghaus stimuli. For example, the Ebbinghaus illusion has close ties to the Delboeuf illusion (Delboeuf, 1865; i.e., an optical illusion of size in which two identical circles are placed near each other, and one is surrounded by an annulus: the surrounded circle appears larger if the annulus is close, but it appears smaller if the annulus is distant; Girgus et al., 1972; Girgus & Coren, 1982), and developmental studies on this illusion also do not consider the role of literacy, even though the biggest differences are similarly found between preschool and school years (e.g. Weintraub & Cooper, 1972). At the limit, the role of literacy should be considered for any visual task that relies on visual integration abilites, particularly when that visual integration can be carried out by early visual areas.

In conclusion, we have shown that learning to read impacts the susceptibility to a specific visual illusion of size, the Ebbinghaus illusion. This was evident both with adults and children. Adult readers, that is, ex-illiterate and literate, were more susceptible to this illusion compared to illiterate adults. First-grade children learning to read were also more susceptible to this illusion compared to age matched pre-literate preschoolers with the same cognitive abilities. Therefore, we suggest that literacy contributes to visual integration abilities, likely through strengthening horizontal connections that link cells within the primary visual cortex.

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